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ELASTIC AND ELASTIC-PLASTIC FRACTURE TOUGHNESS

K.J. KarisAllen

FACTS ENGINEERING INC.

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ABSTRACT

Material temperature transition curves are a necessary requirement for the understanding of the response of structures exposed to various temperatures, loading rates, and stress states. DREA has relied heavily on ASTM standard E-604 to produce transition information for steels and weldments of relevance to the Canadian Navy. This report focuses on the relationship between ASTM E-604 transition curves and quantitative elastic and elastic-plastic fracture properties, namely, K and J-integral, respectively. The materials evaluated include marine steel plates and weldments with varying flow properties, including Lloyds Grade A plate, CSA G40.21 350WT, and ASTM A517. A comparison of the ASTM E-604 transition temperature and the transition temperature for specimens tested at quasistatic loading rates indicates a significant shift to lower transition temperatures for the quasistatic specimens. This shift was attributed to the difference in applied loading rates between the two tests. Elastic and elastic-plastic analyses of the 350WT and A517 test samples indicate that as the temperature decreases, the failure mechanism changes from ductile stable limit load tearing to brittle unstable crack propagation. There was no temperature interval for the materials in the thicknesses tested where crack initiation was governed by either K or J as defined by ASTM E-399 and ASTM E-813, respectively.

The Lloyds Grade A plate material in the T-L orientation produced J controlled crack initiation down to -55°C. For the L-T orientation, the specimen tested at 0°C generated crack extensions by limit load tearing. In the temperature interval from -20°C to -40°C, the specimen produced J controlled crack initiation. The specimens tested at -55°C and -70°C initiated brittle instabilities after significant plasticity.

RÉSUMÉ

Il est nécessaire d'avoir des courbes de transition de température des matériaux pour pouvoir comprendre la réaction des structures exposées à différentes températures, différents taux de charge et différents états de contrainte. Le CRDA utilisait surtout la norme ASTM E-604 pour obtenir des données sur la transition des soudures et des aciers utilisés dans la marine canadienne. Le présent rapport traite de la relation entre les courbes de transition de la norme ASTM E-604 et les propriétés quantitatives de rupture élastique et élastique-plastique, à savoir K et intégrale J respectivement. Les matériaux évalués incluent des plaques en acier et des assemblages soudés possédant différentes propriétés d'écoulement, y compris une plaque de nuance A Lloyds, un échantillon de matériau de type 350 WT de la norme CSA G40-21 et un échantillon de matériau conforme à la norme ASTM A517. Une comparaison de la température de transition de la norme ASTM E-604 et de la température de transition des échantillons mis à l'essai à des taux de charge quasi statiques indique un changement important vers les températures de transition inférieures pour les échantillons quasi statiques. Ce changement est attribuable à la différence de charge appliquée lors des deux essais. Les analyses élastiques et élastiques-plastiques de l'échantillon d'essai de type 350 WT et de celui conforme à la norme A517 indiquent qu'à mesure de la température diminue, le mécanisme de défaillance passe de charge limite de déchirement ductile stable à propagation de fissure instable par fragilisation. Il n'y avait pas d'intervalle de température pour les épaisseurs de matériaux mis à l'essai où l'amorçage de la fissuration était gouvernée par K ou J selon les définitions des normes ASTM E-399 et ASTM E-813 respectivement.

Le matériau de la plaque de nuance A Lloyds dans le sens T-L présentait un amorçage de fissuration contrôlée J jusqu'à -55 °C. Dans le sens L-T, l'échantillon mis à l'essai à 0 °C présentait un allongement de fissure par charge limite de déchirement. Dans l'intervalle de température de -20 °C à -40 °C, l'échantillon présentait un amorçage de fissuration contrôlée J. Les échantillons mis à l'essai à -55 °C et -70 °C présentaient des instabilités par fragilisation après une plasticité importante.

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1.0 INTRODUCTION

Material temperature transition curves are a necessary requirement for the understanding of the response of structures exposed to various temperatures, loading rates, and stress states. DREA has relied heavily on ASTM standard E-604 to produce transition information for steels and weldments of relevance to the Canadian Navy. This report focuses on looking at the relationship between ASTM E-604 transition curves and quantitative elastic and elastic-plastic fracture properties, namely, K and J-integral, respectively. The materials evaluated include marine steel plates and weldments with varying flow properties. The next section provides a background to the work carried out during this study.

2.0 TECHNICAL BACKGROUND

Several test procedures have been incorporated into standardized test methods for the development of temperature transition curves. The most commonly used procedure is ASTM E-23 [1] which is commonly referred to as the Charpy V-notch test method. The Charpy V-notch is a dynamic test which uses a 10 mm x 10 mm x 55 mm bend bar with a shallow 2 mm machined notch. The root tip radius of this notch is 0.25 mm. The energy required to fracture the specimens is recorded for various temperatures. This data is used to generate a temperature transition curve.

The dynamic tear test developed by US naval researchers was standardized into ASTM E-604 [2]. The E-604 specimen is significantly larger than the E-23 specimen (16 mm x 40.62 mm x 181mm) providing increased lateral and back face constraint as opposed to the E-23 specimen. The 12 mm notch in this specimen is pressed with a hardened knife to increase the severity of the crack tip stress intensity factor. Similar to the E-23 test method, the fracture energy required to fail the specimen at various temperatures is used as the data for developing the material transition curve.

Drop-weight tear testing of ferritic steels (ASTM E-436 [3]) provides a visual method for determining the transition behaviour of materials. A 75 mm x 300 mm specimen x the as received thickness of the plate is impacted at dynamic loading rates. A shallow pressed notch is created on the tension surface to initiate the fracture event. The standard uses the percent area of cleavage fracture to determine the transition characteristics of a material.

The specimen configuration of the nil ductility test method (ASTM E208 [4]) is substantially different than the above described test methods. The specimen thickness to height of this specimen is 3.5/1 (in all the above procedures, the thickness to height is less than 1/1). This specimen incorporates a brittle starter notch to initiate the fracture. As opposed to getting a complete transition curve, this test method is used to define the nil ductility temperature (NDT) at which complete lateral cracking occurs across the specimen.

A relatively recent unstandardized test procedure for the generation of transition curves is the measurement of the residual shear lip created by the fracture process[5,6]. The specimen geometry used is the same as ASTM E-604. Numerous studies have shown that the shear lip width correlates well to fracture energy. Intuitively, shear lip width should also correlate well with crack arrest toughness, K_a, since it is measured at a point on the fracture surface where a brittle crack is dominating the fracture process. This test also has the added advantage that it does not require the expensive instrumentation of tests such as E-604.

The test procedures described above produce transition curves which may be significantly different. A significant temperature shift can occur when comparing DT energy and shear lip transition curves to Charpy V-notch transition curves [7]. Studies have shown that a good correlation exists between DT and shear lip transition curves to precracked specimens impacted at dynamic loading rates[5,6]. The lower transition temperature generated by Charpy V-notch specimens is attributed to the lack of specimen capacity owing to specimen size and notch acuity differences[7]. Since transition information is generated as an indicator of structural performance, the DT geometry will provide a relationship closer to the structural response.

Numerous studies have investigated the correlation between the CVN impact energy and quasistatic fracture toughness [8,9]. The studies primarily focus on the relationship between K_{IC} and CVN energy. An investigation has also been conducted into the relationship between the CTOD and the NDT. The current study evaluates several marine steel plates and weldments with a focus of relating the validity of quantitative initiation fracture toughness procedures such as K and J-integral to the lower knee of the DT temperature transition curve. For specimens which generate brittle instabilities without significant ductile crack extension, shear lip width will be correlated to the elastic fracture toughness parameter K.

3.0 EXPERIMENTAL

3.1 Specimen Preparation

Thirty specimens were provided by DREA/DL for evaluation in this study. A listing of the specimens received for testing together with the ASTM E-604 lower knee transition temperatures determined by DREA/DL are given in Table 1 as follows:

Table 1 - Specimens received from DREA for testing.

Material	Orientation	Transition Temp ©	Total No.
Lloyds Grade A	T-L	10	5
Lloyds Grade A	L-T	0	5
12mm 350WT	T-L	-45	3
12mm 350WT	L-T	-45	2
8mm 350WT	T-L	-30	3
8mm 350WT	L-T	-40	2
10mm A517	T-L	-45	3
10mm A517	L-T	-55	2
Weld Series 3	N/A	0	1
Weld Series 11	N/A	-25	1
Weld Series 12	N/A	-15	2
Weld Series 20	N/A	-30	1

Received specimen dimensions were measured for compliance with ASTM E-604. Specimen thickness (B) was the as received thickness of the plate. To accommodate the clip gauge required for fatigue precracking, integral knife edges were machined into the lateral faces of the specimen notch at the lower surface of the specimen (Figure 1). Also, specimens were drilled and tapped for support posts used to attach a load-line displacement sensor to the specimen. Prior to testing, notch tips of the specimens were precompressed to 40 percent of the limit load as defined by ASTM E-1152 and subsequently fatigue precracked to a depth of approximately .55 a/W using an R ratio of 0.1 and a maximum stress intensity factor of 30 MPa$\sqrt{m}$.

3.2 Test Procedure

Specimens were tested at quasistatic loading rates using a fully automated servo-hydraulic materials test system. Prior to loading, each specimen was positioned on the three point bend fixture. Next, the control software applied a compressive pre-load to the specimen to fix it in place while the environmental chamber cooled the specimen to the

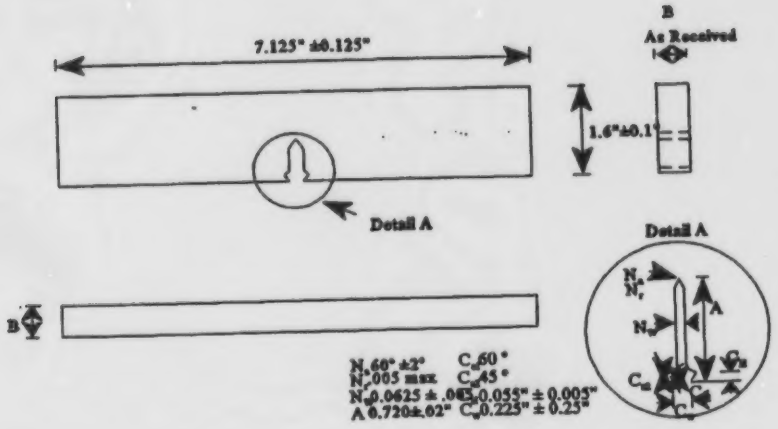

Figure 1 - Specimen geometry showing integral knife edges machined into the specimen.

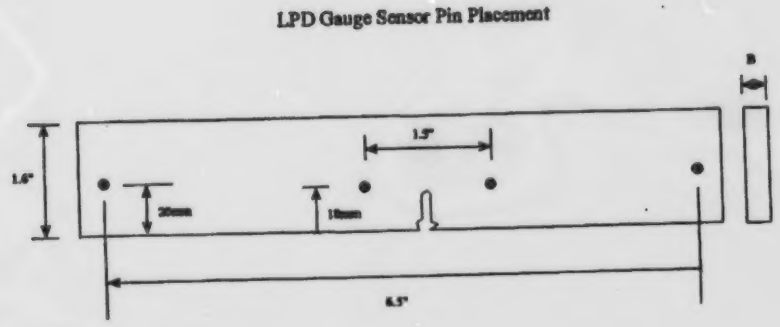

Figure 2 - Specimen geometry showing location of supports for specimen mounted load-line displacement gauge.

desired test temperature. Specimens were soaked at the predetermined test temperature for a minimum of 15 minutes before the testing sequence was activated. The testing sequence employed a monotonic loading rate of 0.005 mm/s. For the first ten cycles, the loading cycle was interrupted at 0.1mm intervals for the unload/reload sequence required to obtain crack extension information. After the first ten cycles, the cycle interval was increased to 0.2 mm. Analog signals generated from an instrumented load cell, COD clip gauge, and remote ram LVDT were digitized using a 14 bit A/D converter and stored in a microprocessor for further analysis.

3.3 Data Analysis

Collected data was analysed for elastic and elastic plastic behaviour using ASTM E-399 and E-813, respectively. An elastic analysis in accordance with ASTM E-399 requires a load-displacement record in order to establish a K_Q value. A linear least squares fit of the initial portion of the curve was used to establish the slope of the load displacement data. A check for linearity was performed by establishing a regression correlation coefficient between the data set and the calculated slope. A regression coefficient in excess of 0.997 usually indicates a suitable correlation. The software program subsequently calculated the 95 percent secant line and then iterated through the load displacement data set to establish the P_Q value. K_Q is calculated from the P_Q value using the relationship published in E-399 for bend bars loaded in three point bending. Validity of the K_Q value was established by comparing the specimen capacity to the applied K_Q value (applied K_Q must be lower than the specimen capacity). Compliance with the fatigue crack straightness criteria was established by physical measurement of the fatigue crack on the specimen fracture surface at 3 locations. If both specimen capacity and crack front straightness criteria were met, K_Q was reported as a valid K_{IC}.

An elastic-plastic analysis performed in accordance with ASTM E-813 requires a load/load-line displacement record and a means of periodically establishing the crack length at various intervals during the test. Unloading compliance was used as the method of determining crack extension, requiring a load/COD record with unloading and reloading sequences. At each unloading, applied J and crack length were calculated in accordance with the methodology published in E-813. Once the J-Δa relationship was obtained, the points contained within the 0.15 mm blunting line offset and the 1.5 mm blunting line offset capped by the J capacity for the specimen were regressed using a least squares fit to a power law function. If a minimum of 4 points do not lie within this predescribed area, J-Δa values for the specimen tested cannot be used to establish an initiation elastic plastic fracture value (J_Q) in accordance with this standard. The intersection of the calculated power law with the 0.2 mm offset generates the value of J_Q. Similar to K_Q, if J_Q meets the specimen capacity and crack front straightness criteria, J_Q can be reported as a J_{IC} value.

4.0 RESULTS

4.1 General

Four distinctly different types of fracture behaviour were observed for the specimens tested during this study. With reference to Figures 4.1 to 4.4, these differing behaviours are described as:

a) Type I - Limit load tearing (LLT) - This fracture behaviour produces only limited amounts of crack extension with calculated applied J values above the upper capacity of the specimen for J controlled growth (Figure 4.1).

b) Type II - J-controlled crack extension (J_Q) - This fracture behaviour generates crack extension within the J-Δa couplet requirements of ASTM E-813 (Figure 4.2).

c) Type III - Initiation of a brittle instability after limited amounts of ductile crack extension (Figure 4.3). The load/displacement record for this type of fracture reveals significant plasticity with calculated applied J values at initiation above the J capacity of the specimen.

d) Type IV - Initiation of a brittle instability off a blunted crack front (Figure 4.4). Load displacement records for these specimens indicate that limit load has not been attained. Applied stress intensity for these specimens can be calculated as a K value or a J value, depending on meeting respective validity criteria as set out in the standard.

It is also relevant in this general presentation of the results to comment on the various problems encountered with the sensors located within the environmental chamber at low temperatures during this study. Both the load line bend bar and the COD gauge showed significant thermal/noise problems at temperatures below -55 °C. Figures 4.5 to 4.7 show similar sections of a specimen load displacement record for a specimen tested at - 65 °C for remote LVDT, specimen attached COD, and specimen attached bend bar, respectively. Both the COD and load line bend bar show significant visual deviations from linearity (hysteresis). The remote LVDT did not exhibit this problem indicating that the problem resided with the sensors contained within the environmental chamber. Several additional procedures were thus applied to the data during the analysis to ensure the accuracy of the results. These included;

a) Analysing the ASTM E-399 results using machine compliance corrected LVDT displacement [10] as opposed to COD displacement. This step ensures that all specimens were analysed using the same sensor for displacement. The change from COD displacement to LVDT displacement does not effect the determination of K_Q insofar as the standard only requires a measure of displacement to construct a 0.95 secant line. The position of the intersection of the 0.95 v/p secant line with the load displacement data will be unaffected by this measure.

b) Compliance corrected LVDT data was employed for the energy calculation in ASTM E-813 [11].

c) In order to ensure accurate crack extension data, only load/COD unloadings with a least squares correlation coefficient exceeding 0.999 were allowed for crack length determination.

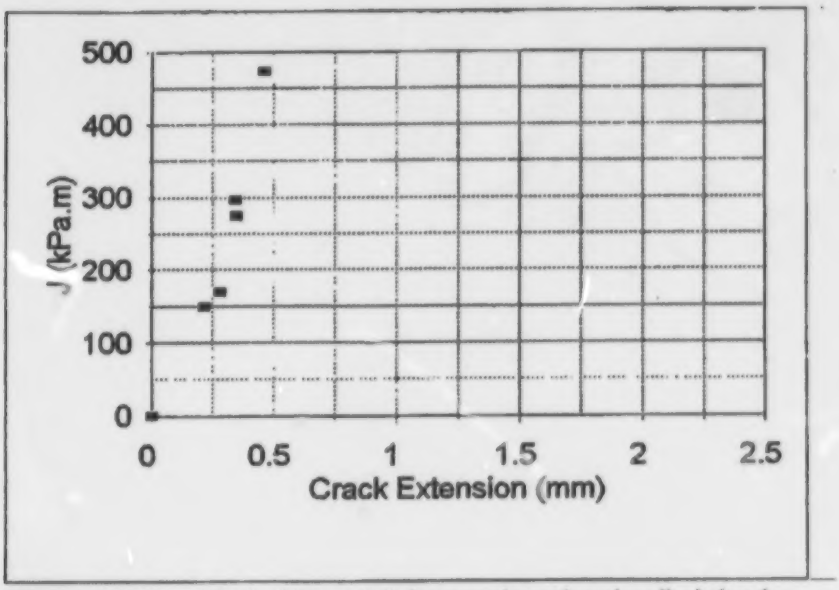

Figure 4.1(a) - Typical Type I J-Δa couplets showing limit load tearing data (specimen #96).

Figure 4.1(b) - Photograph showing the fracture appearance of 12 mm 350WT L-T specimen #89 tested at -45 ^{0}C (Type I fracture).

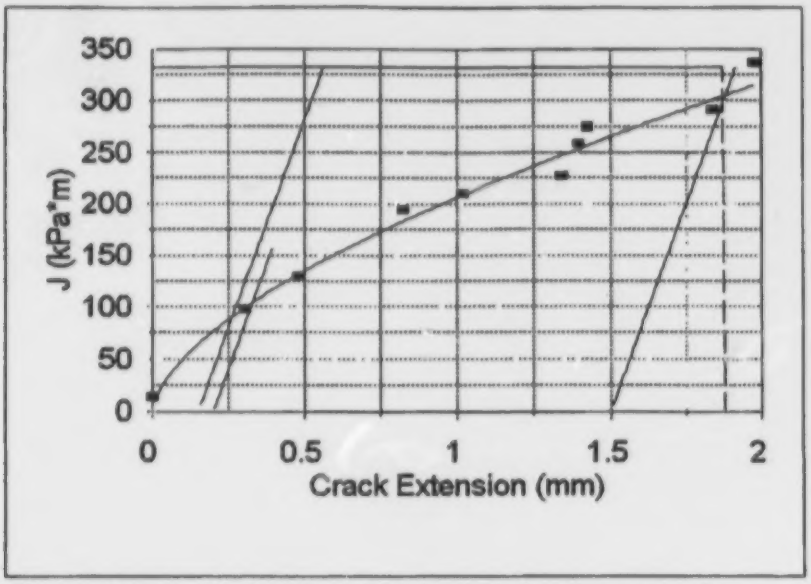

Figure 4.2(a) - Typical Type II J-Δa data showing power law resistance curve in conformance with ASTM E813 (specimen #96).

Figure 4.2(b) - Photograph showing the fracture appearance of Lloyds Grade A T-L specimen #96 tested at -45 ^{0}C (Type I fracture).

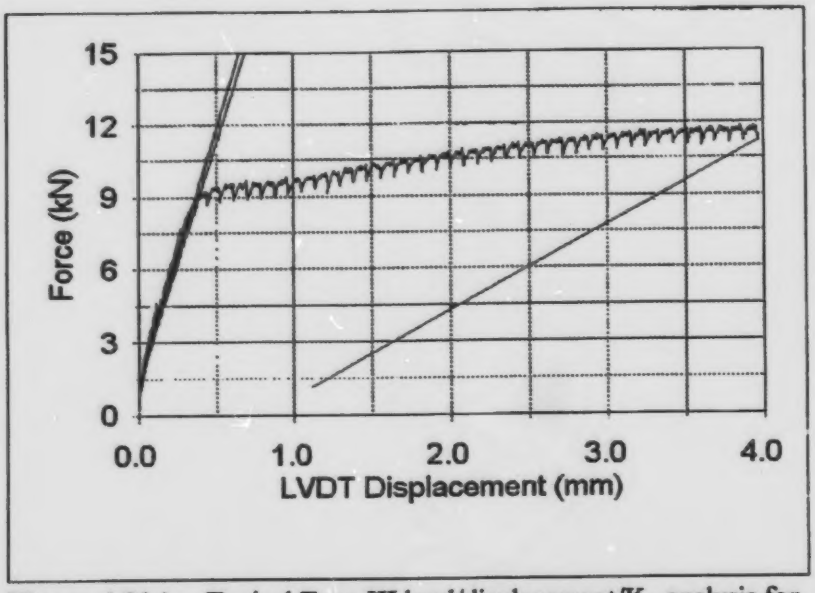

Figure 4.3(a) - Typical Type III load/displacement/K_Q analysis for initiation of a brittle instability after limited amounts of ductile crack extension (specimen #80).

Figure 4.3(b) -Photograph showing the fracture appearance of Lloyds Grade A L-T specimen #80 tested at -40 ^{0}C (Type III fracture).

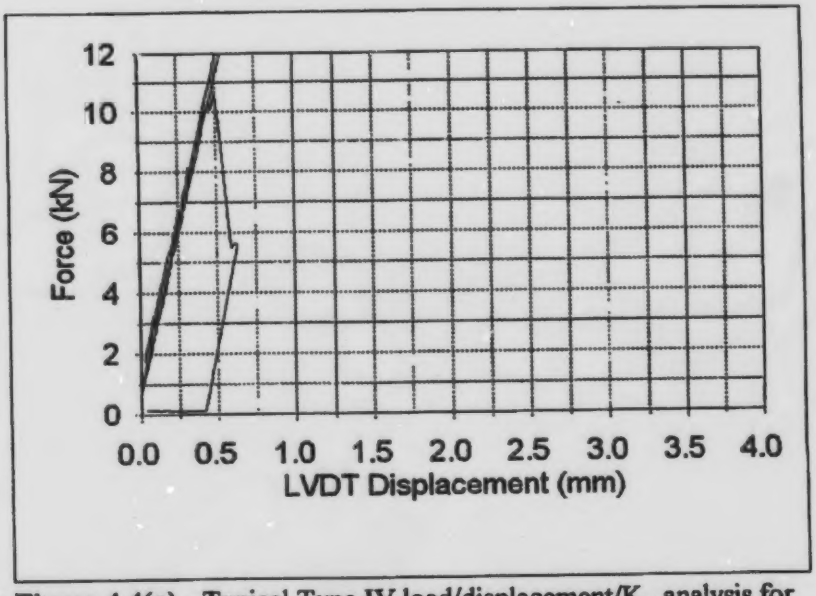

Figure 4.4(a) - Typical Type IV load/displacement/K_Q analysis for initiation of a brittle instability with no ductile crack extension (specimen #82).

Figure 4.4(b) - Photograph showing the fracture appearance of weldment series 12 specimen #82 tested at -50 ^{0}C (Type IV fracture).

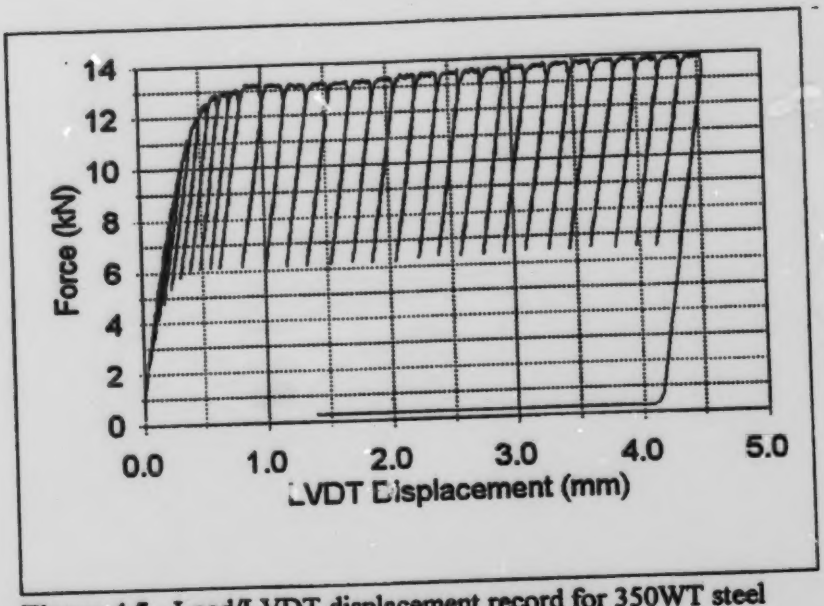

Figure 4.5 - Load/LVDT displacement record for 350WT steel specimen tested at -65 °C (T-L orientation).

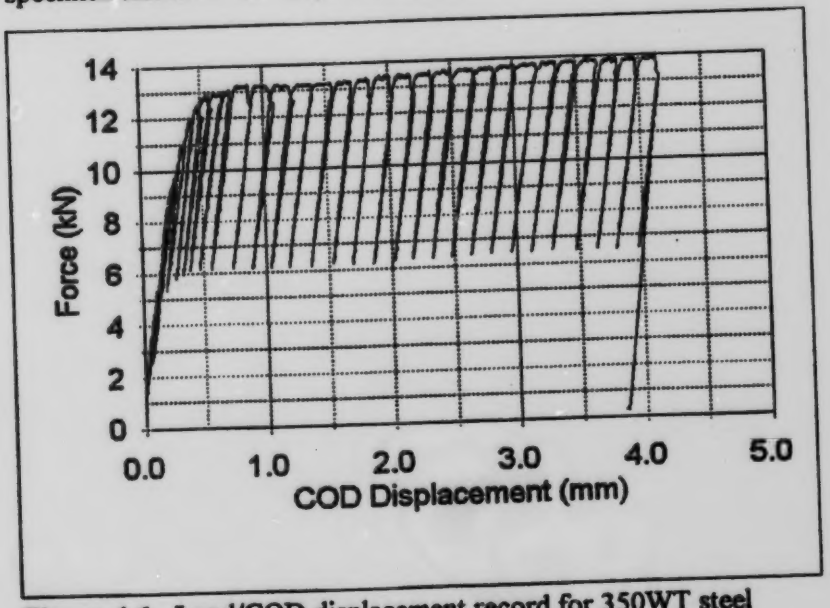

Figure 4.6 - Load/COD displacement record for 350WT steel specimen tested at -65 °C (T-L orientation).

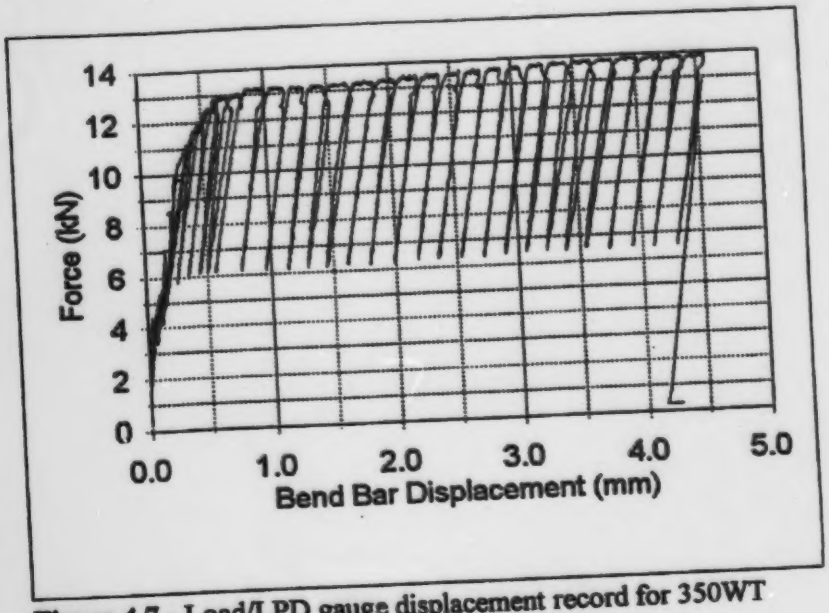

Figure 4.7 - Load/LPD gauge displacement record for 350WT steel specimen tested at -65 °C (T-L orientation).

4.2 Lloyds Grade A Steel Plate Results

Appendices A and B contain the load/LVDT displacement and the load/COD displacement for the Lloyds Grade A material tested in the T-L and L-T orientation respectively. Appendix J contains the ASTM E-399 results generated for the load/LVDT displacement data. Appendix O contains the ASTM E-813 J-resistance curves for the test which generated the appropriate number of valid data points. Table 4.1 summarizes the ASTM E-399 results contained in Appendix J. For the T-L orientation, K_Q values increased from 39.7 Mpa$\sqrt{m}$ to 50.7 Mpa$\sqrt{m}$ as temperatures decreased from 22 °C to -55 °C. P_{max}/P_Q values for these specimens decreased as temperature decreased. The specimens with the notch orientation in the L-T direction generated similar K_Q with no clear trend observed in the data. Similarly, the P_{max}/P_Q ratios did not provide evidence of change with temperature. None of the Lloyds Grade A T-L or L-T specimens produced valid plane strain fracture toughness values between the temperatures of 0 °C and -70 °C. While some of the low toughness specimens met through thickness constraint and remaining ligament constraint, none met the P_{max}/P_Q requirements. The significant plasticity sustained by these specimens as evidenced in their load/displacement confirms that crack extension is not K controlled in these fracture tests (even when initiated brittle instabilities exhibited significant plasticity prior to brittle initiation).

Table 4.1 - Summary of ASTM E399 results for Lloyds Grade A steel

Specimen ID	Material	Orientation	Temp °C	P_Q (Mpa√m	P_{max}/P_Q	Validity Conformance
100	Lloyds Grade A	T-L	22	39.73	1.31	No
99	Lloyds Grade A	T-L	0	41.40	1.28	No
96	Lloyds Grade A	T-L	-22	44.23	1.23	No
81	Lloyds Grade A	T-L	-40	47.32	1.19	No
102	Lloyds Grade A	T-L	-55	50.70	1.14	No
98	Lloyds Grade A	L-T	0	45.32	1.39	No
95	Lloyds Grade A	L-T	-20	44.18	1.47	No
80	Lloyds Grade A	L-T	-40	50.11	1.29	No
101	Lloyds Grade A	L-T	-55	43.39	1.59	No
103	Lloyds Grade A	L-T	-70	46.31	1.39	No

Table 4.2 summarizes the ASTM E-813 results for the Lloyds Grade A specimens which generated the required J-Δa couplets within the 0.15 mm and 1.5 mm offsets and capped by J_{max}. For specimens with their notch orientation in the T-L direction, J_Q values decrease with decreasing temperature. The exception to this trend was the specimen tested at 22 °C. By observing the J-resistance curve generated for this specimen, it can be seen that the initial blunting points indicate that the J_Q value should be higher than that generated by the power law regression through the J-Δa couplets contained within the required area for valid points. In this case, the procedure outlined by E-813 produced a highly conservative J_Q value. The specimens with notch orientated in the L-T direction exhibited limit load tearing at 0 °C. The specimens tested at -20 °C and -40 °C produced the appropriate J-Δa couplets required to conduct an analysis according to E-813. L-T specimens tested at -55 °C and -70 °C produced J_Q values at the brittle instabilities of 431 kPa.m and 212 kPa.m, respectively. Both these specimens exhibited limited degree ductile crack extension prior to initiating the instability. With the exception of the L-T specimen tested at 0 °C, all the Lloyds Grade A specimens met the remaining ligament and through thickness constraint criteria in accordance with the standard. Of these specimens, the only specimens which did not provide valid J_{IC} values were specimens which did not meet the crack front straightness criteria (many of these specimens show varying degrees of tunnelling).

Table 4.2 - Summary of ASTM E-813 results for Lloyds Grade A steel

Specimen ID	Material	Orientation	Temp °C	J_Q (Mpa√m	Validity Conformance
100	Lloyds Grade A	T-L	22	85.23	No
99	Lloyds Grade A	T-L	0	157.35	Yes
96	Lloyds Grade A	T-L	-22	104.12	No
81	Lloyds Grade A	T-L	-40	105.85	Yes
102	Lloyds Grade A	T-L	-55	45.40	No
95	Lloyds Grade A	L-T	-20	115.30	No
80	Lloyds Grade A	L-T	-40	186.30	No

4.3 CSA G40.21 350WT 12 mm Steel Plate Results

Appendices C and D contain the load/LVDT displacement and the load/COD displacement for the 12 mm thick CSA G40.21 350WT material tested in the T-L and L-T orientation, respectively. Appendix K contains the ASTM E-399 results generated for the load/LVDT displacement data. Table 4.3 summarizes the ASTM E-399 results contained in Appendix K. For the T-L orientation, K_Q values decreased from 64.28 MPa√m to 44.51 MPa√m as temperatures decreased from -45 °C to -95 °C. P_{max}/P_Q values for these specimens increased as temperature decreased. The specimens with the notch orientation in the L-T direction generated K_Q values which increased from 61.16 Mpa√m at -45 °C to 72.05 Mpa√m at -95 °C. The P_{max}/P_Q ratios did not provide evidence of change with temperature. None of the 350WT T-L or L-T specimens produced valid plane strain fracture toughness values between the temperatures of -45 °C and -95 °C. None of the specimens met through thickness constraint and remaining ligament constraint, none met the P_{max}/P_Q requirements. The significant plasticity sustained by these specimens as evidenced in their load/displacement confirms that crack extension is not K controlled in these fracture tests (the T-L specimen which initiated a brittle instability at -95 °C exhibited significant plasticity).

Table 4.3 - Summary of ASTM E-399 results for 12 mm CSA G40.21 350WT steel

Specimen ID	Material	Orientation	Temp °C	P_Q (Mpa√m)	P_{max}/P_Q	Validity Conformance
88	12 mm 350WT	T-L	-45	64.28	1.25	No
92	12 mm 350WT	T-L	-65	58.70	1.39	No
107	12 mm 350WT	T-L	-95	44.51	1.94	No
89	12 mm 350WT	L-T	-45	61.16	1.30	No
108	12 mm 350WT	L-T	-95	72.05	1.27	No

With the exception of the T-L specimen tested at -95 °C, all the 12 mm 350WT specimens experienced limit load tearing. A typical applied J-Δa plot for this material was shown in Figure 4.1. It can be seen from this data that all the J-Δa couplets generated by this specimen reside outside the required area for calculating a J_Q value in accordance with E-813. The T-L specimen which generated a brittle instability at -95 °C developed an applied J value of 229 kPa.m.

4.4 CSA G40.21 350WT 8 mm Steel Plate Results

Appendices E and F contain the load/LVDT displacement and the load/COD displacement for the 8mm CSA G40.21 350WT material tested in the T-L and L-T orientation, respectively. Appendix L contains the ASTM E-399 results generated for the load/LVDT displacement data. Table 4.4 summarizes the ASTM E-399 results contained in Appendix L. For the T-L orientation, K_Q values decreased from 68.70 MPa√m to 56.74 MPa√m as temperatures decreased from -10 °C to -35 °C. P_{max}/P_Q values for these specimens increased as temperature decreased. The specimens with the notch orientation in the L-T direction generated K_Q values which remained relatively unchanged for the tests conducted at -35 °C and -50 °C. None of the 350WT T-L or L-T specimens produced valid plane strain fracture toughness values between the temperatures of -10 °C and -50 °C. None of the specimens met through thickness constraint and remaining ligament constraint, none met the P_{max}/P_Q requirements. The significant plasticity sustained by these specimens as evidenced in their load/displacement confirms that crack extension is not K controlled in these fracture tests (the T-L specimen which initiated a brittle instability at -50 °C exhibited significant plasticity).

Table 4.4 - Summary of ASTM E-399 results for 8 mm CSA G40.21 350WT steel

Specimen ID	Material	Orientation	Temp °C	P_Q (Mpa√m)	P_{max}/P_Q	Validity Conformance
97	8 mm 350WT	T-L	-10	68.70	1.12	No
93**	8 mm 350WT	T-L	-25	62.54	1.30	No
94	8 mm 350WT	T-L	-35	56.74	1.51	No
90	8 mm 350WT	L-T	-35	56.71	1.41	No
91	8 mm 350WT	L-T	-50	54.34	1.73	No

4.5 ASTM A517 10 mm Steel Plate Results

Appendices G and H contain the load/LVDT displacement and the load/COD displacement for the 10 mm ASTM A517 material tested in the T-L and L-T orientation, respectively. Appendix M contains the results for the ASTM E-399 generated for the load/LVDT displacement data. Table 4.5 summarizes the ASTM E-399 results contained in Appendix M. For the T-L orientation, K_Q values varied between 94.65 MPa√m to 117.52 MPa√m as temperatures decreased from -45 °C to -95 °C. P_{max}/P_Q values for these specimens also varied with test temperature. The specimens with the notch orientation in the L-T direction generated K_Q values which remained relatively

Table 4.5 - Summary of ASTM E-399 results for 10 mm ASTM A517 steel

Specimen ID	Material	Orientation	Temp °C	P_Q (Mpa√m)	P_{max}/P_Q	Validity Conformance
84	10 mm A517	T-L	-45	94.65	1.32	No
110	10 mm A517	T-L	-75	117.52	1.16	No
105	10 mm A517	T-L	-95	107.30	1.32	No
90	10 mm A517	L-T	-55	110.13	1.22	No
109	10 mm A517	L-T	-95	115.84	1.23	No

unchanged for the tests conducted at -55 °C and -95 °C. None of the 350WT T-L or L-T specimens produced valid plane strain fracture toughness values between the temperatures of -45 °C and -95 °C. None of the specimens met through thickness constraint and remaining ligament constraint, none met the P_{max}/P_Q requirements. The significant plasticity sustained by these specimens as evidenced in their load/displacement confirms that crack extension is not K controlled in these fracture tests (the L-T specimen at -95 °Cand the T-L specimen at -70 °C which initiated brittle instabilities exhibited significant plasticity).

4.6 350WT and A517 Weldment Results

Appendix I contains the load/LVDT displacement and the load/COD displacement for the CSA G40.21 350WT A517 weldments tested. Appendix N contains the ASTM E-399 results generated for the load/LVDT displacement data. Table 4.9 summarizes the ASTM E399 results contained in Appendix N. The 350WT FCAW weldment (series 12) generates brittle instabilities at both -40 °C and -50 °C. E-399 fracture toughness values for the weldments were 57.97 MPa√m and 63.32 Mpa√m for the specimens tested at -40 °C and -50 °C, respectively. The -50 °C test met the P_Q/P_{max} requirements of E-399 but failed both the through thickness and remaining ligament constraint requirements. The 350 WT SAW weldments, series 3 and 11 produced K_Q values of 47.77 Mpa√m and 73.08 Mpa√m, respectively. The only A517 weldment tested (series 3) produced K_Q values of 82.00 Mpa√m. Weldments from series 3,11, and 20 did not pass the P_{max}/P_Q validity criteria.

Weldment 11 initiated a brittle instability after significant plasticity as evidenced by its load displacement record with a J_B value of 243 kPa.m. Weldment 3 propagated a small amount of crack extension by limit load tearing. The only ASTM A517 weldment tested was a specimen from series 20 which generated J-Δa couplets outside the required area for calculating a J_Q value in accordance with E-813.

Table 4.6 - Summary of ASTM E-399 results for selected weldments

Specimen ID	Material	Orientation	Temp °C	P_Q (Mpa√m)	P_{max}/P_Q	Validity Conformance
85	Weld 3	N/A	-50	47.77	1.95	No
87	Weld 11	N/A	-50	73.08	1.21	No
104	Weld 12	N/A	-40	57.97	1.15	No
82	Weld 12	N/A	-50	63.32	1.01	No
86	Weld 20	N/A	-40	82.00	1.44	No

5.0 DISCUSSION

All the materials tested exhibit a shift to lower temperatures for the ductile to brittle transition. Table 5.1 compares the E-604 procedure results (test rate approximately 5 m/s) and quasistatic fracture tests conducted at a crosshead rate of 0.005 mm/s. For the plate materials, the difference in transition temperature between the two test rates ranges from a low of 20 °C for the 8 mm 350 WT plate to a high of 65 °C for the Lloyds grade A material. For the 350WT weld series 3,11 and 12, the shift varied from a low of 25 °C to a high of 50 °C. For the single A517 weldment, the temperature shift was in excess of 10 °C. The variations in temperature shifts indicates differing rate sensitivities of these materials with respect to initiating brittle instabilities.

Table 5.1 - Specimens received from DREA for testing.

Material	Orientation	E-604 Transition Temp ©	Quasistatic Transition Temp ©	Difference ©
Lloyds Grade A	T-L	10	-55 **	65
Lloyds Grade A	L-T	0	-40	40
12mm 350WT	T-L	-45	-95	50
12mm 350WT	L-T	-45	-95**	50**
8mm 350WT	T-L	-30	-50	20
8mm 350WT	L-T	-40	-35**	N/A
10mm A517	T-L	-45	-75	30
10mm A517	L-T	-55	-95	40
Weld Series 3	N/A	0	-50**	50**
Weld Series 11	N/A	-25	-50*	25*
Weld Series 12	N/A	-15	-40*	25*
Weld Series 20	N/A	-30	-40**	10**

** Specimens tested in this series did not generate ductile crack extension for the temperatures tested. Temperature difference between the two test protocols is lower.

** Specimens tested in this series did not initiate a brittle instability for the temperatures tested. Temperature difference between the two test protocols is higher

Figures 5.1 and 5.2 summarizes the relationship between the applied K_Q and temperature for materials where multiple specimens were tested for the T-L and L-T orientation, respectively. Trends in this relationship for specimens machined in the T-L orientation vary with the Lloyds Grade A material showing an increase in K_Q values with decreasing temperature. The limited number of specimens of series 12 weldments also shows this increasing K_Q trend with decreasing temperature. Both the 12 mm and 8 mm 350WT specimens show decreasing K_Q values with temperature. The trend for the A517 plate material is not clearly defined by this data set.

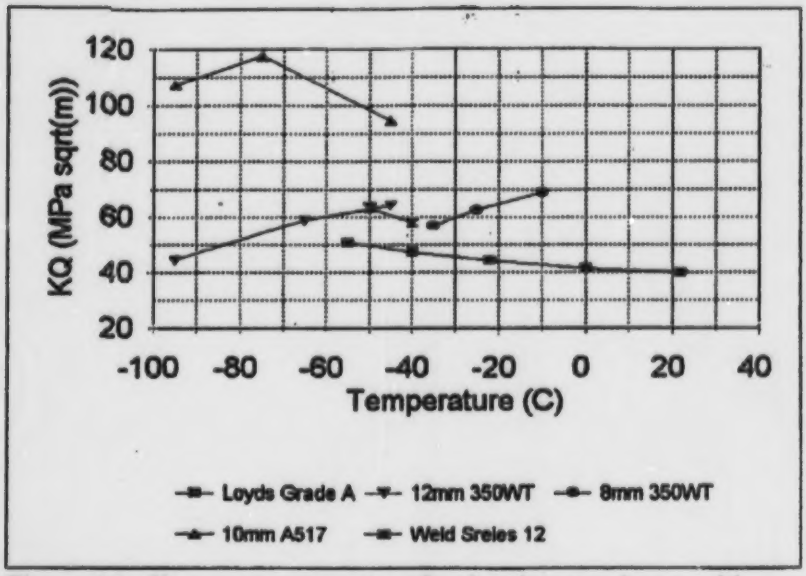

Figure 10 - K_Q verses temperature for the plate specimens with notch orientation in the T-L direction and weld series 12.

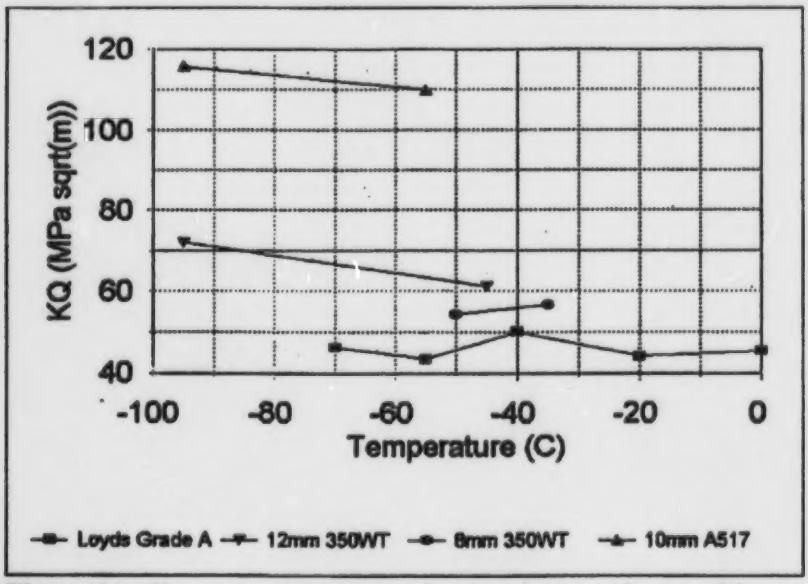

Figure 11 - K_Q verses temperature for the plate specimens with notch orientation in the L-T direction.

In general, the trends for specimens with notch orientation in the L-T direction do not support the data for the same material in the T-L direction. The K_Q for the Lloyds Grade A material remains relatively constant over the temperatures tested. With decreasing temperature, the 12 mm and 8 mm 350WT show increasing and decreasing trends, respectively. The A517 plate results show an increasing trend with decreasing temperature. It should be noted that, except for the Lloyds Grade A material, insufficient sampling of the other materials in the L-T orientation significantly reduces the confidence of the trends generated.

All but one of the specimens tested, specimen #82, failed to meet the P_{max}/P_Q validity requirements in E-399. Also, the lateral constraint requirements which define the capacity of these specimens were not met. The validity of using K as a parameter to describe brittle initiation should also be discussed. ASTM E-399 defined three types of curves for characterizing K_Q values. ASTM E-399 was originally focused on providing K information for materials generating stable crack extensions. The 0.95 percent offset is an attempt to define the point of crack initiation in specimens which show limited amounts of plasticity owing to the contributions from the shear lips. In the case where brittle initiation occurs, the intersection of the 0.95 secant line with the data set may define a point removed from the point where the actual brittle initiation occurs. If and energy based fracture parameter such as J was employed using the same data set and the elastic K_Q value converted to an elastic J_{KQ} value, a comparison of this J_{KQ} value and the 2U/Bb J_Q value would not be in good agreement. Thus, for brittle initiation, only when $P_{max} = P_Q$ (ASTM E-399 Type III curve) would it be expected that J_Q and J_{KQ} would be comparable.

Figure 5.3 summarizes the J_Q verses temperature relationship for the Lloyds Grade A material in the T-L and L-T orientations . Five T-L and two L-T Lloyds Grade A specimens met J-Δa couplet requirements of ASTM E-813. None of the other specimens tested met the J-Δa couplet requirements of E-813. The trend for the J_Q verses temperature for the T-L orientation indicates a decrease in J_Q with temperature (note: section 4.2 indicates the E-813 procedure produced an overly conservative value of J_Q at 22 °C). For the L-T orientation, while the data indicates that the J_Q value increases with temperature between -20 °C and -40 °C, too few data points were gathered to have a high degree of confidence in this trend. For the Lloyds Grade A specimens, as the test temperature decreased, ductile J controlled crack extension was replaced by brittle instabilities. While the L-T orientation provided superior toughness for ductile crack extension, it initiated brittle instabilities at higher temperatures when compared to the T-L specimens.

For high toughness welds (series 3 and 20) and steel materials (350WT and A517), the data indicates that the specimen goes from conditions of limit load tearing to initiating brittle instabilities without any temperature interval of stable J controlled ductile crack extension. High toughness combined with the lack of lateral constraint on these specimens leads to the lack of any temperature interval of J controlled initiation toughness in these materials.

Figure 5.4 shows the correlation between K_Q and shear lip for all the specimens which initiated brittle instabilities without any significant ductile crack growth. The data indicates that in general, the shear lip associated with the propagation of a brittle instability decreases with K_Q.

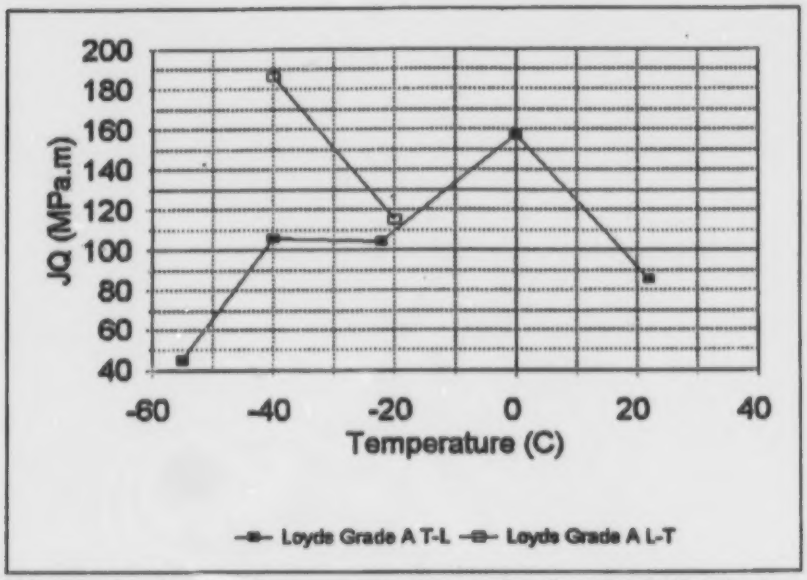

Figure 12 - Applied J versus temperature for the Lloyds Grade A material for T-L and L-T notch orientations.

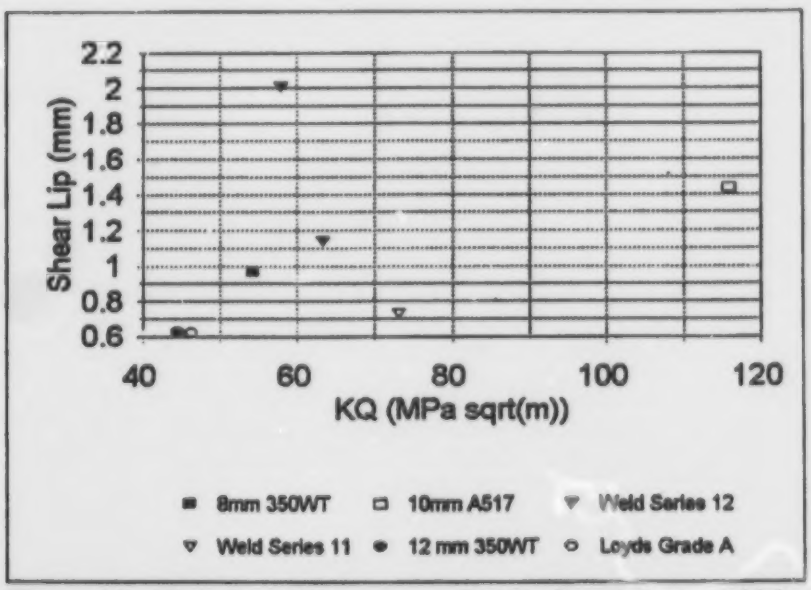

Figure 13 - Shear lip width verses applied K_Q for specimens which initiated brittle instabilities prior to ductule crack extension.

6.0 CONCLUSIONS

The current study focuses on the relationship between ASTM E-604 transition curves and quantitative elastic and elastic-plastic fracture properties, namely, K and J-integral, respectively. The materials evaluated include marine steel plates and weldments with varying flow properties. The following inferences can be concluded from the data generated in this report:

1) All the materials tested with quasistatic loading rates exhibited a shift to lower temperatures for the ductile to brittle transition when compared to the lower knee of the E-604 transition curve. This phenomna was attributed to rate sensitivities of the various materials tested.

2) Of the materials tested only the series weld 12 tested at -50 °C produced a K_Q value which met the P_{max}/P_Q validity requirements of ASTM E-399. It has also been concluded that for specimens which initiate brittle instabilities, only Type III curves as defined by ASTM E-399 should be used in a linear elastic analysis.

3) For the T-L orientation, K_Q values increased with decreasing temperature for the Lloyds Grade A plate and weldment series 12. In both 8 mm and 12 mm 350 WT E-399 analyses, K_Q values decreased with decreasing temperatures. Specimens with the notch orientation in the L-T orientation exhibited relatively constant K_Q values over the temperature tested.

4) Only the Lloyds Grade A material tested contained an interval where slow stable J controlled crack growth was observed.

5) 350WT and the A517 specimens generated either limit load tearing or initiation of a brittle instability over the temperatures tested.

6) In general, shear lip width measured adjacent to a propagating brittle fracture decreases with calculated K_Q values.

Since many of the material sets contained too few samples to generate a high degree of confidence in the observed trends, it is recommended that additional samples be tested and analysed to establish these trends.

7.0 REFERENCES

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2. "Standard Test Method for Dynamic Tear Testing of Metallic Materials," Annual Book of ASTM Standards, vol. 3.01, 1997.

3. "Standard Test Method for Drop-Weight Tear Tests of Ferritic Steels," Annual Book of ASTM Standards, vol. 3.01, 1997.

4. "Standard Test Methods for Conducting Drop-Weight Test to Determine Nil-Ductility Transition Temperature of Ferritic Steels," Annual Book of ASTM Standards, vol. 3.01, 1997.

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6. Matthew, J.R., E.J. Robichaud, V. Roy and C.V. Hyatt, "Dynamic Tear Structural Transition Determination for Steel and Weldments Removed from HMCS Calgary," DREA Note No. DL(A)/98/7.

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11. "Standard Test Methods for J_{IC}, A Measure of Fracture Toughness," Annual Book of ASTM Standards, vol. 3.01, 1997.

Appendix A - Data Records for Lloyds Grade A Steel (T-L Orientation)

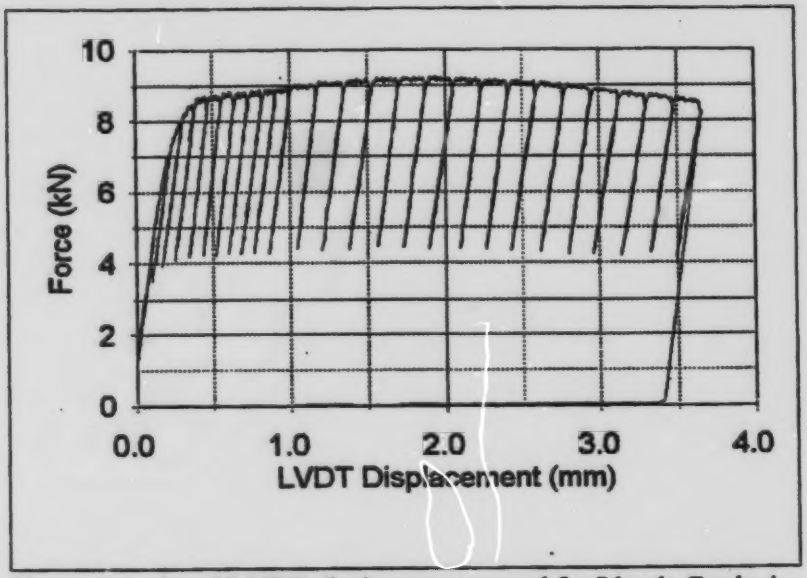

Figure A.1 - Load/LVDT displacement record for Lloyds Grade A steel specimen #100 at 22°C.

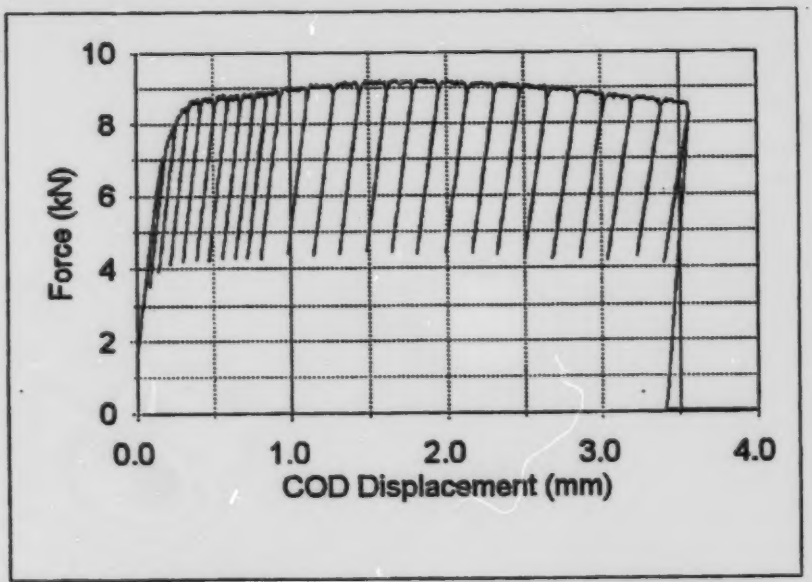

Figure A.2 - Load/COD displacement record for Lloyds Grade A steel specimen #100 at 22°C.

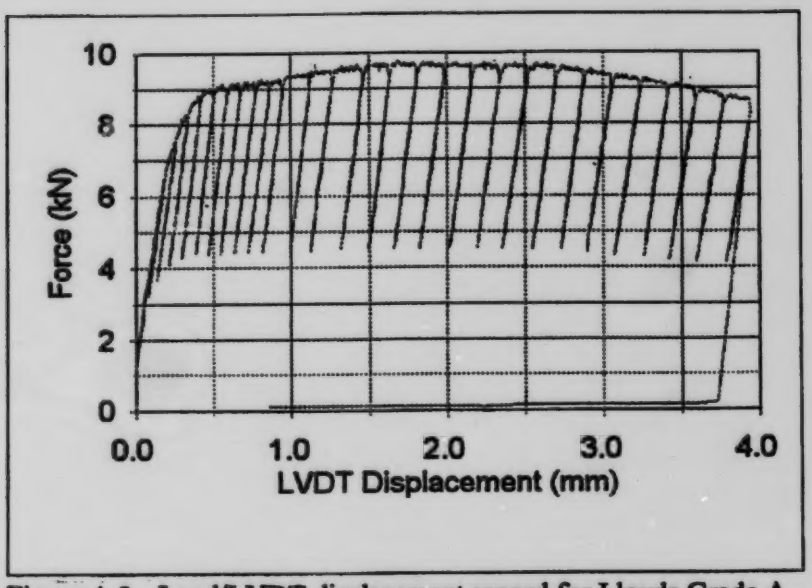

Figure A.3 - Load/LVDT displacement record for Lloyds Grade A steel specimen #99 at 0°C.

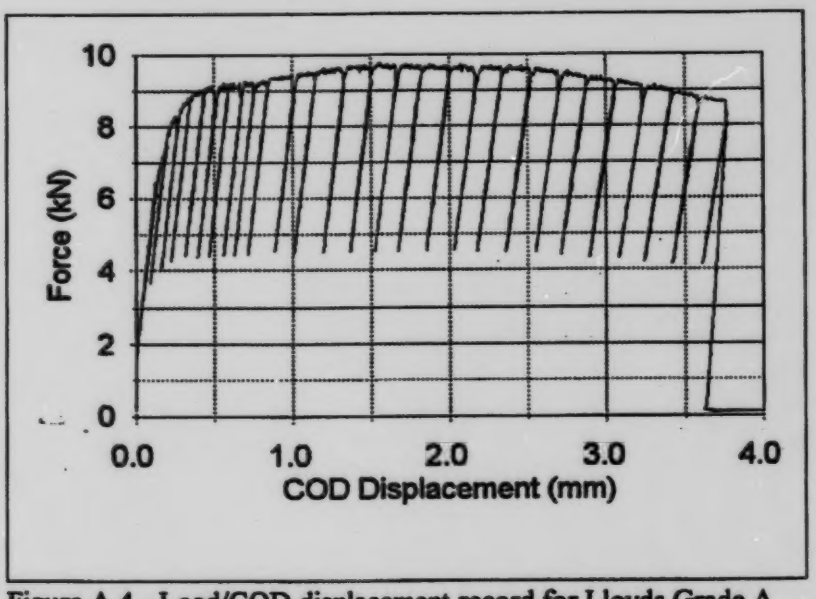

Figure A.4 - Load/COD displacement record for Lloyds Grade A steel specimen #99 at 0°C.

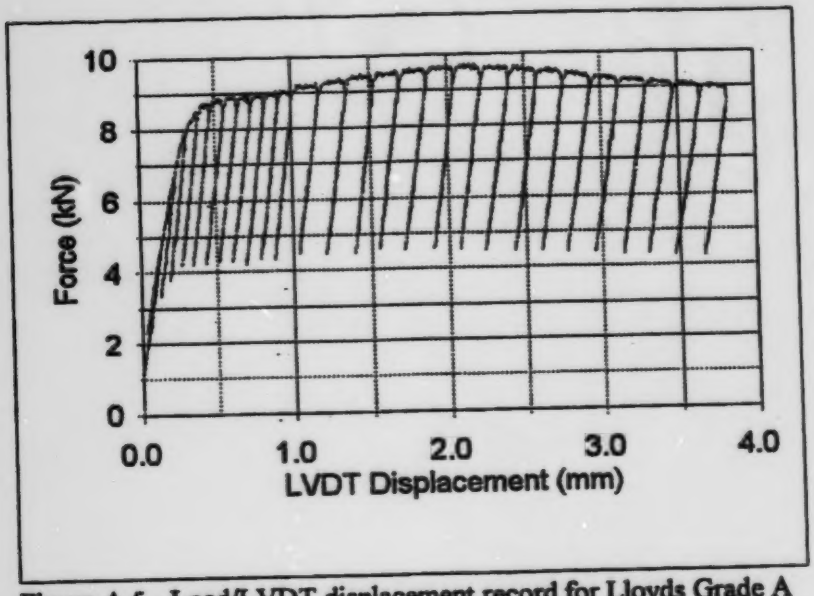

Figure A.5 - Load/LVDT displacement record for Lloyds Grade A steel specimen #96 at -20°C.

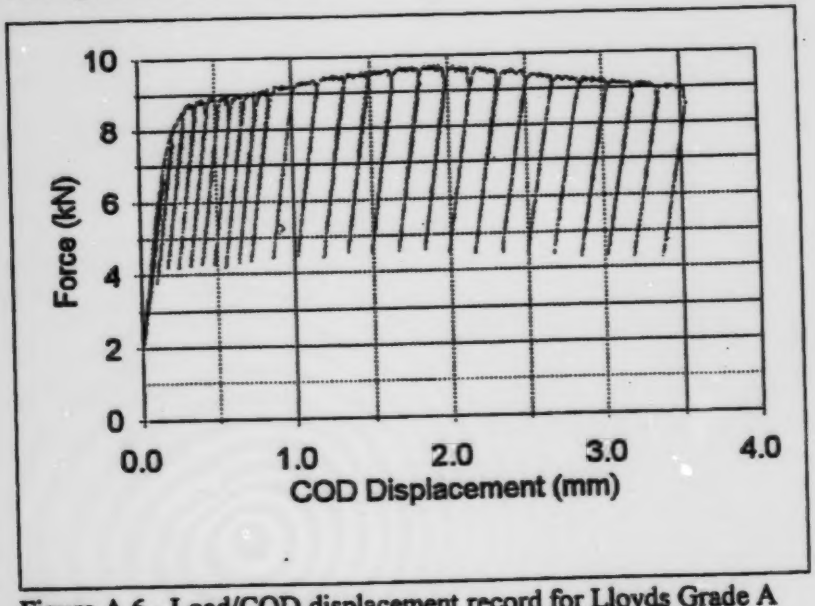

Figure A.6 - Load/COD displacement record for Lloyds Grade A steel specimen #96 at -20°C.

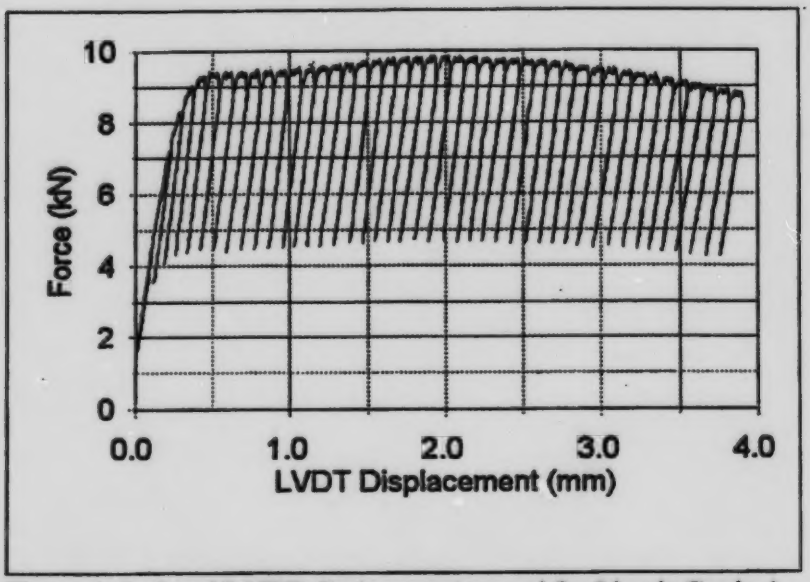

Figure A.7 - Load/LVDT displacement record for Lloyds Grade A steel specimen #81 at -40°C.

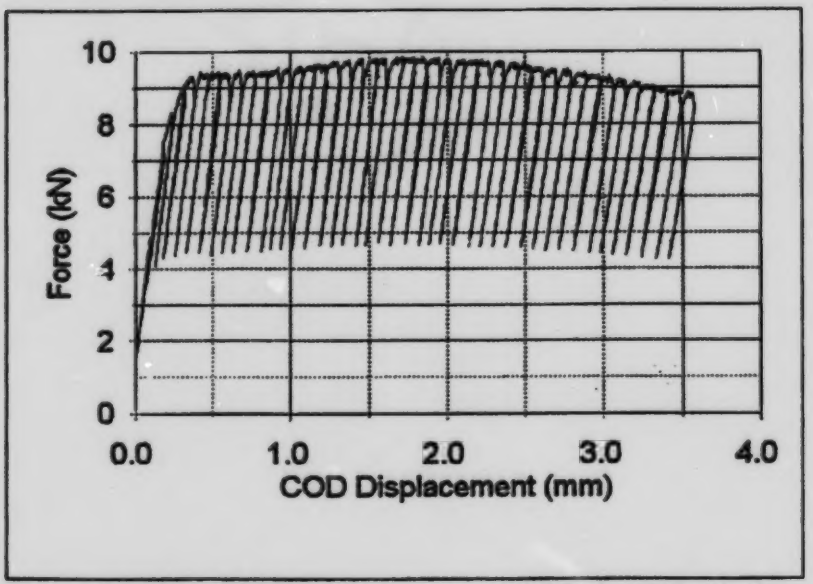

Figure A.8 - Load/COD displacement record for Lloyds Grade A steel specimen #81 at -40°C.

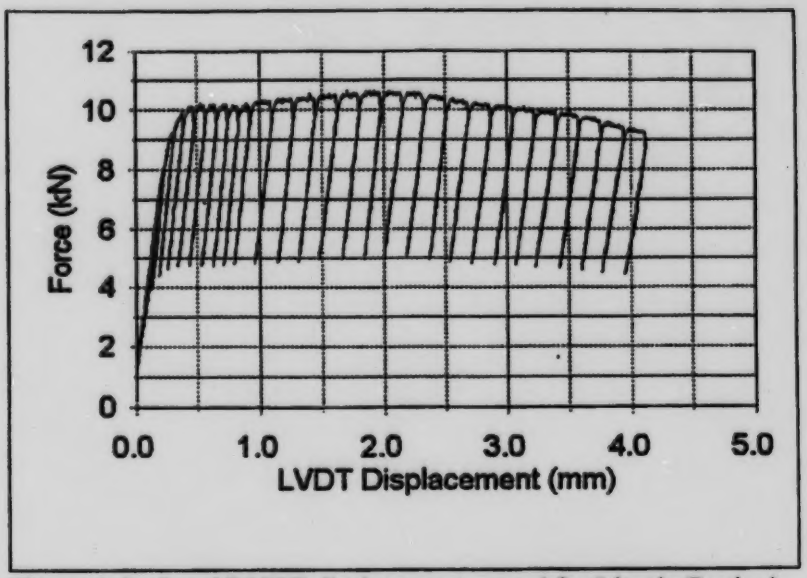

Figure A.9 - Load/LVDT displacement record for Lloyds Grade A steel specimen #102 at -55°C.

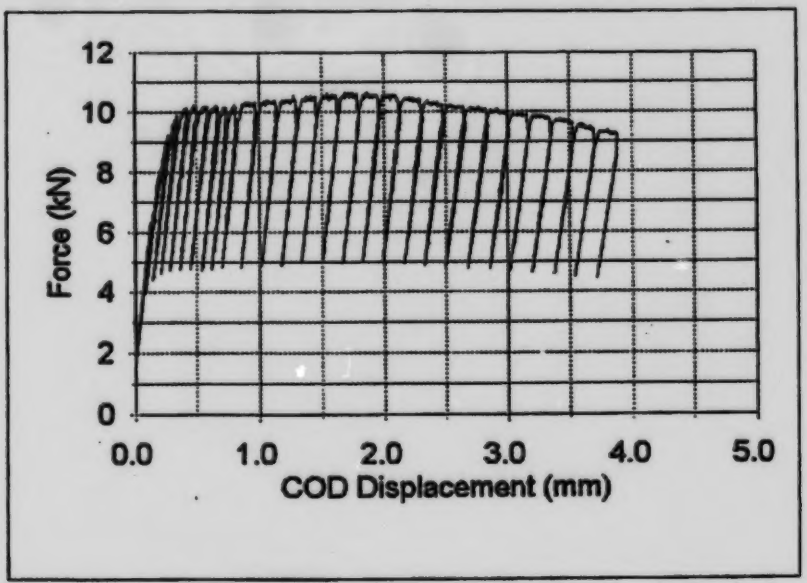

Figure A.10 - Load/COD displacement record for Lloyds Grade A steel specimen #102 at -55°C.

Appendix B- Data Records for Lloyds Grade A Steel (L-T Orientation)

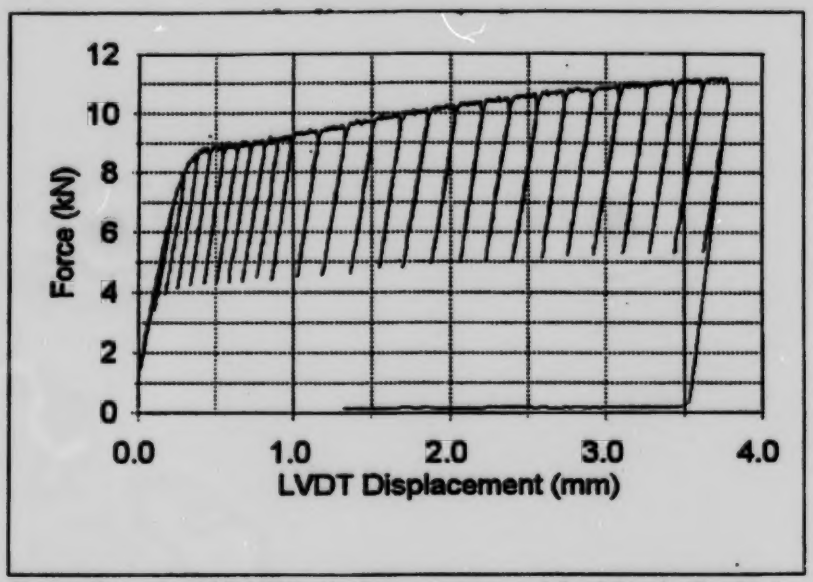

Figure B.1 - Load/LVDT displacement record for Lloyds Grade A steel specimen #98 at 0°C.

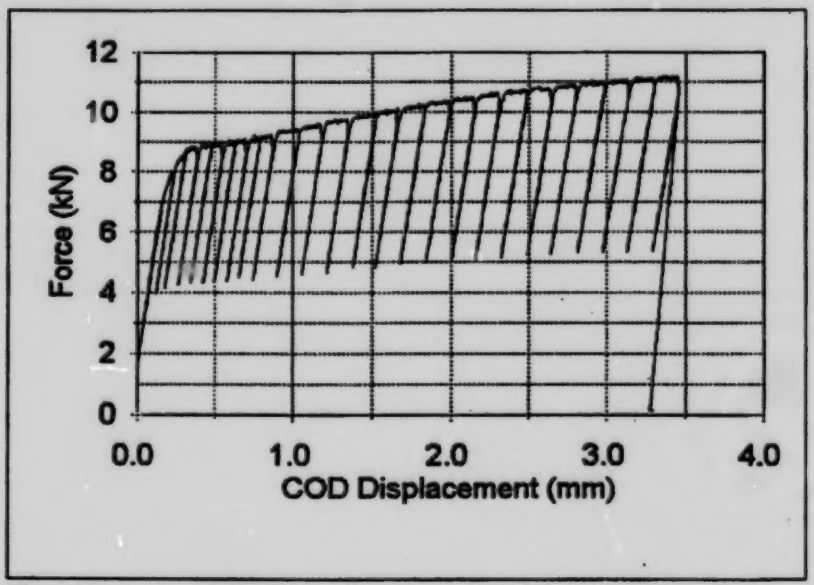

Figure B.2 - Load/COD displacement record for Lloyds Grade A steel specimen #98 at 0°C.

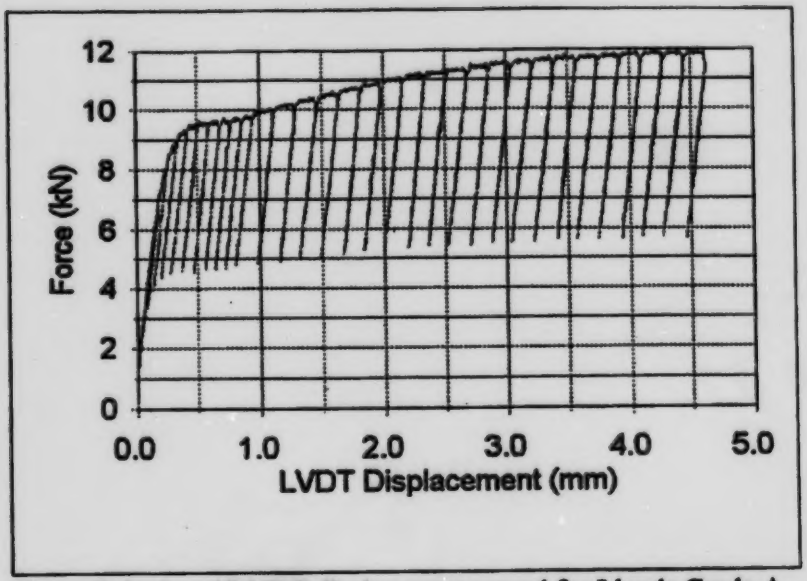

Figure B.3 - Load/LVDT displacement record for Lloyds Grade A steel specimen #95 at -20°C.

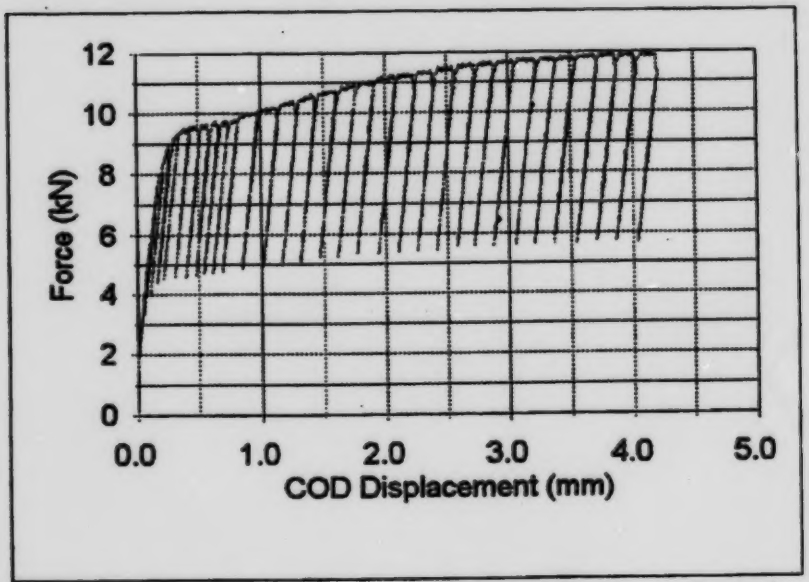

Figure B.4 - Load/COD Displacement Record for Lloyds Grade A steel specimen #95 at -20°C.

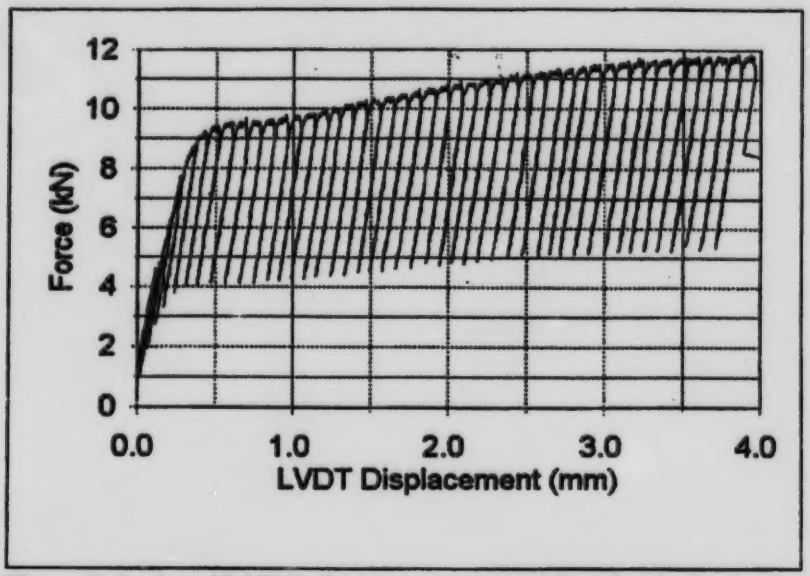

Figure B.5 - Load/LVDT displacement record for Lloyds Grade A steel specimen #80 at -40°C.

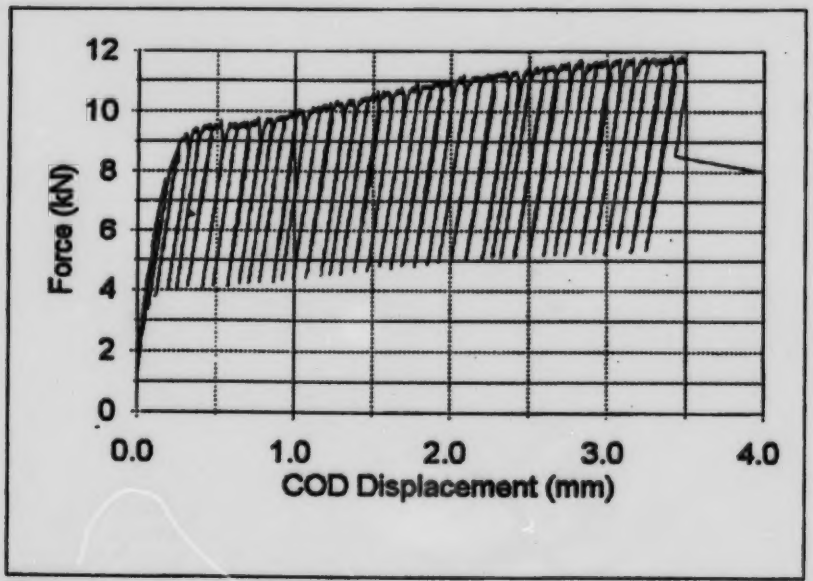

Figure B.6 - Load/COD displacement record for Lloyds Grade A steel specimen #80 at -40°C.

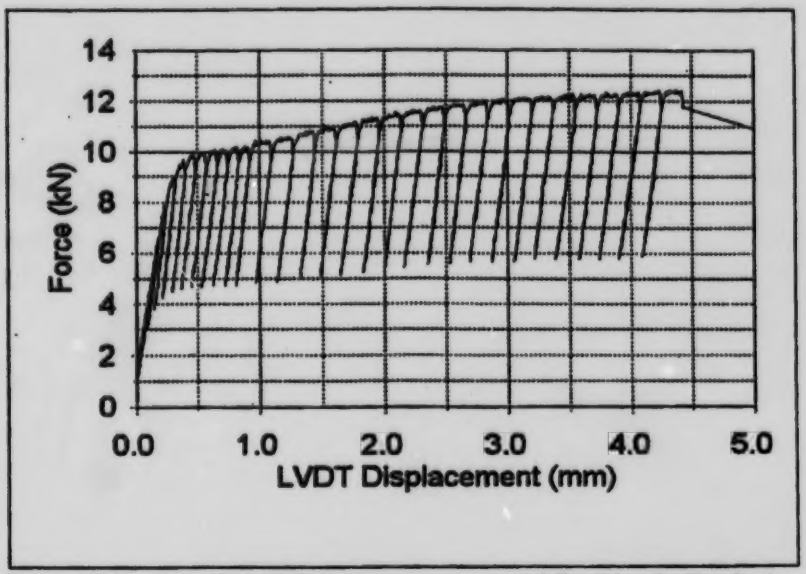

Figure B.7 - Load/LVDT displacement record for Lloyds Grade A steel specimen #101 at -55°C.

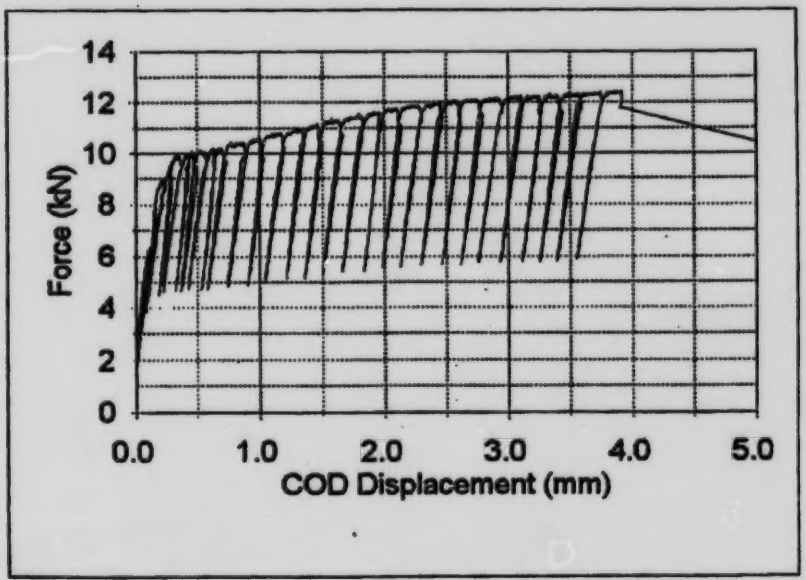

Figure B.8 - Load/COD displacement record for Lloyds Grade A steel specimen #101 at -55°C.

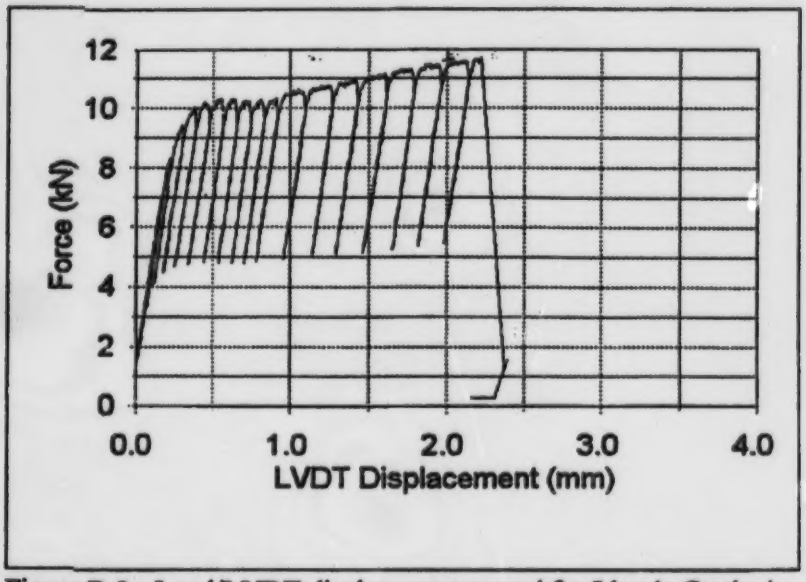

Figure B.9 - Load/LVDT displacement record for Lloyds Grade A steel specimen #103 at -70°C.

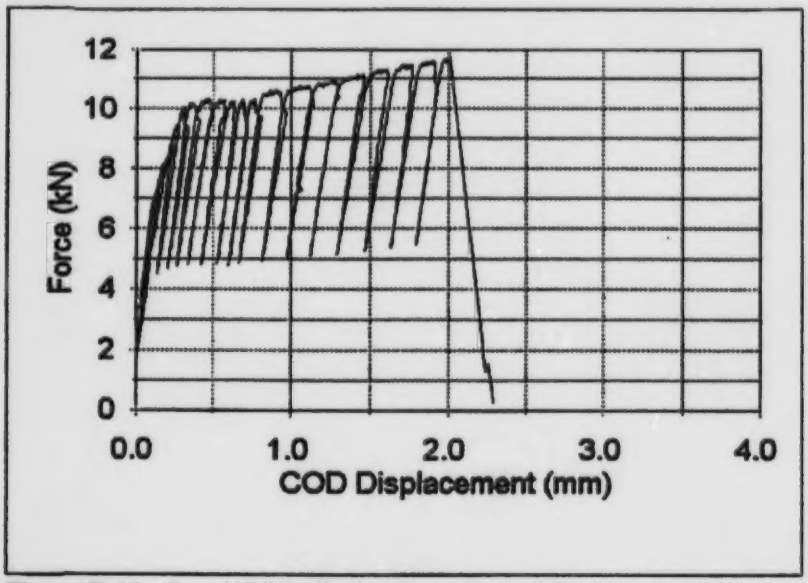

Figure B.10 - Load/COD displacement record for Lloyds Grade A steel specimen #103 at -70°C.

Appendix C - Data Records for 12 mm 350 WT Steel (T-L Orientation)

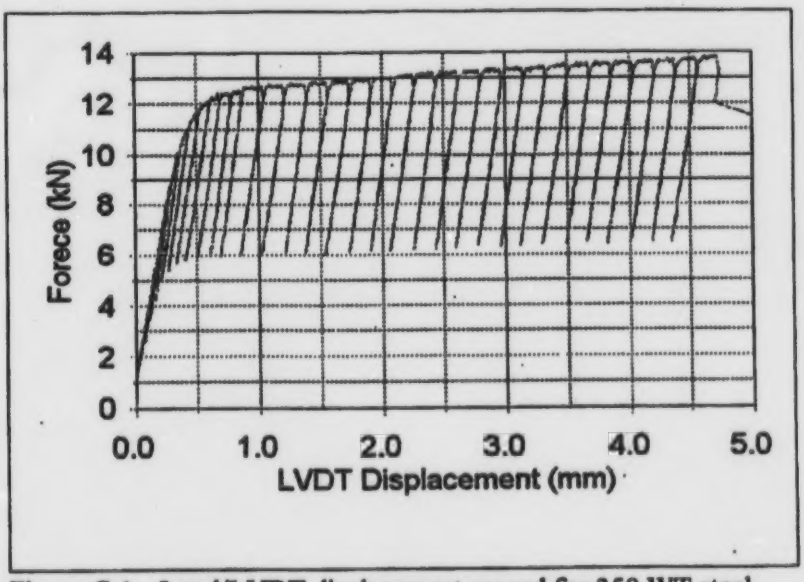

Figure C.1 - Load/LVDT displacement record for 350 WT steel specimen #88 at -45°C.

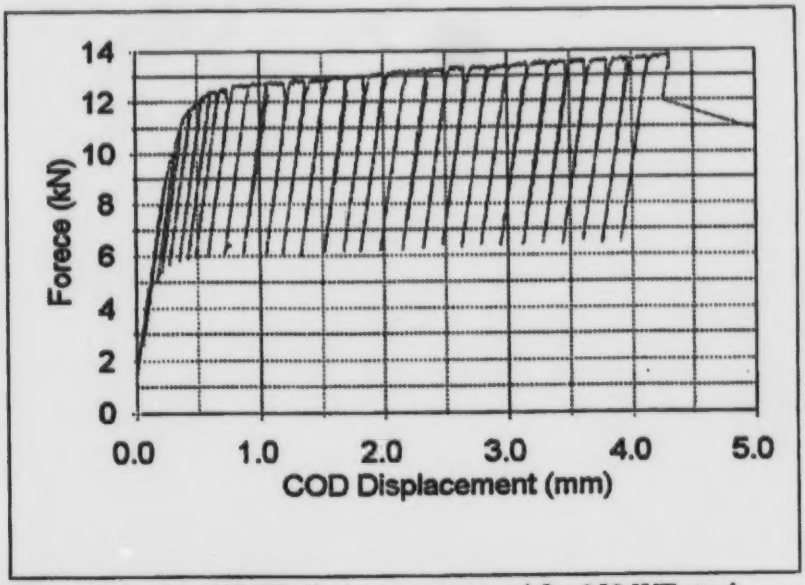

Figure C.2 - Load/COD displacement record for 350 WT steel specimen #88 at -45°C.

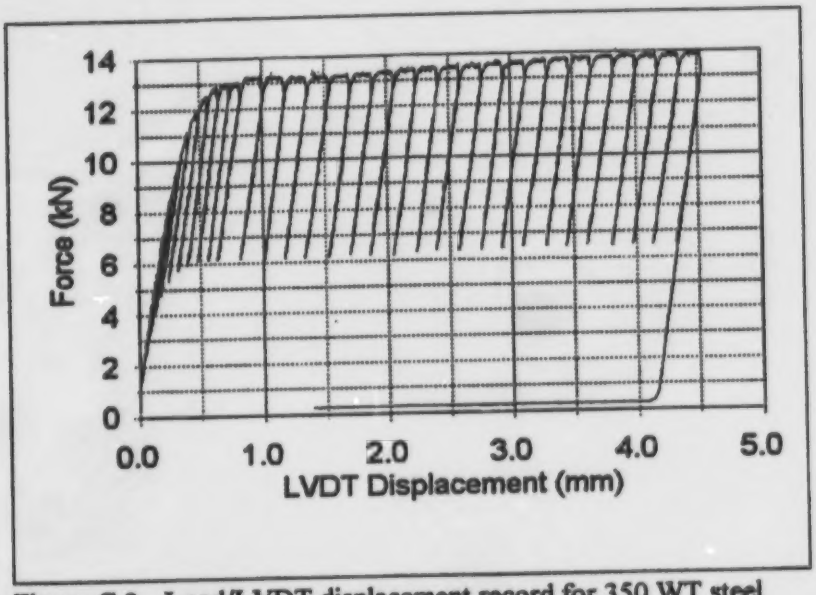

Figure C.3 - Load/LVDT displacement record for 350 WT steel specimen #92 at -65°C.

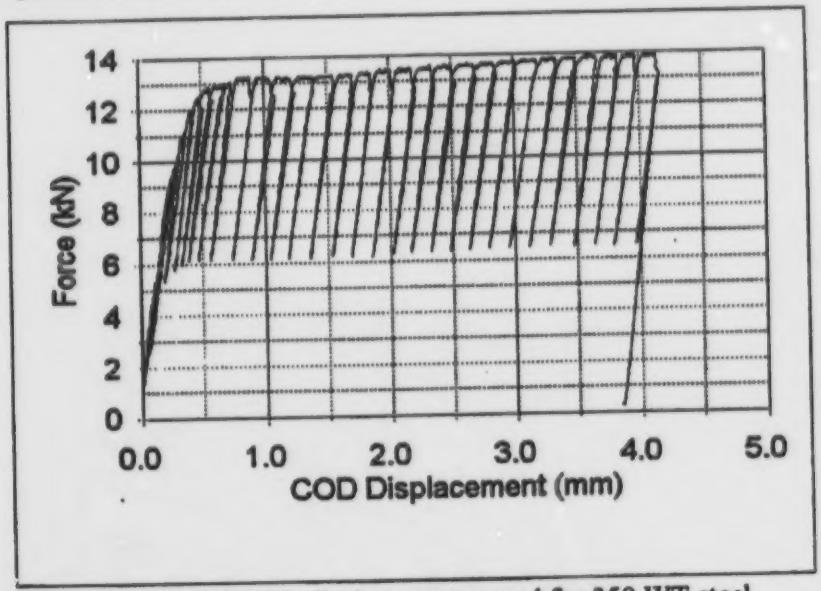

Figure C.4 - Load/COD displacement record for 350 WT steel specimen #92 at -65°C.

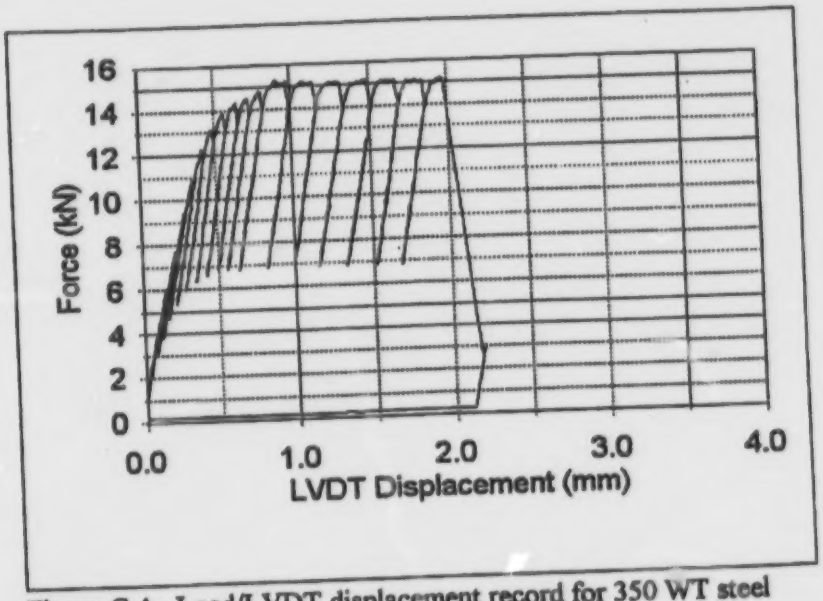

Figure C.4 - Load/LVDT displacement record for 350 WT steel specimen #107 at -95°C.

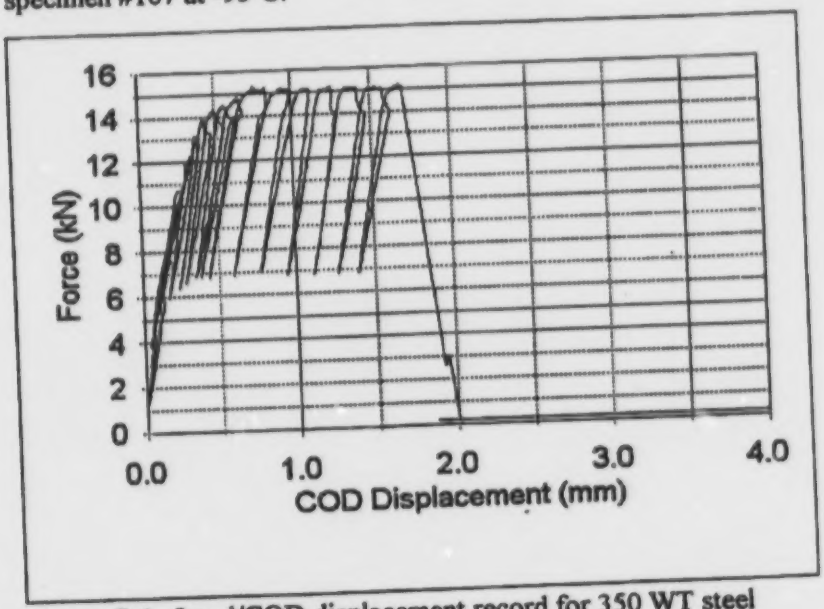

Figure C.6 - Load/COD displacement record for 350 WT steel specimen #107 at -95°C.

Appendix D - Data Records for 12 mm 350 WT Steel (L-T Orientation)

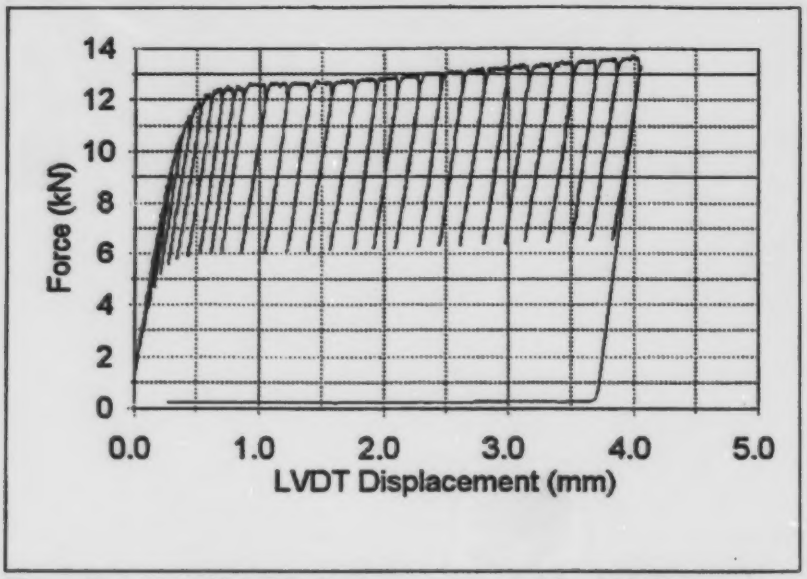

Figure D.1 - Load/LVDT displacement record for 350 WT steel specimen #89 at -45°C.

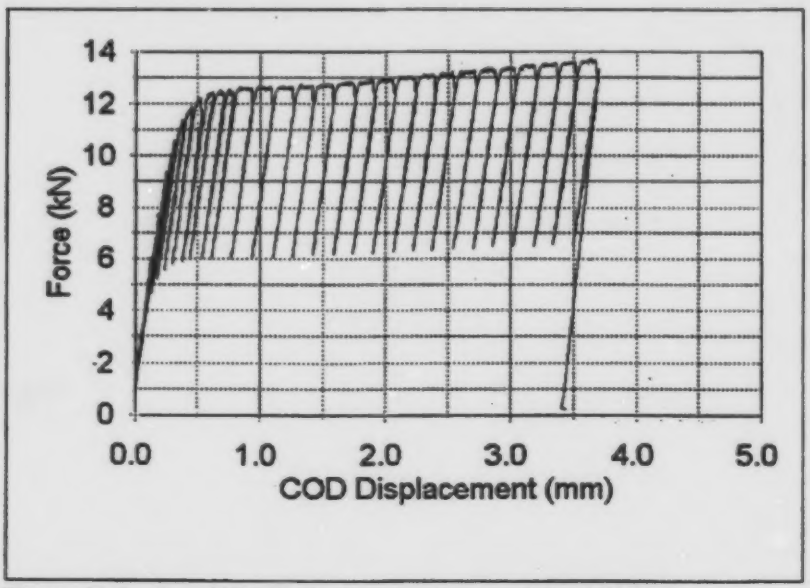

Figure D.2 - Load/COD displacement record for 350 WT steel specimen #89 at -45°C.

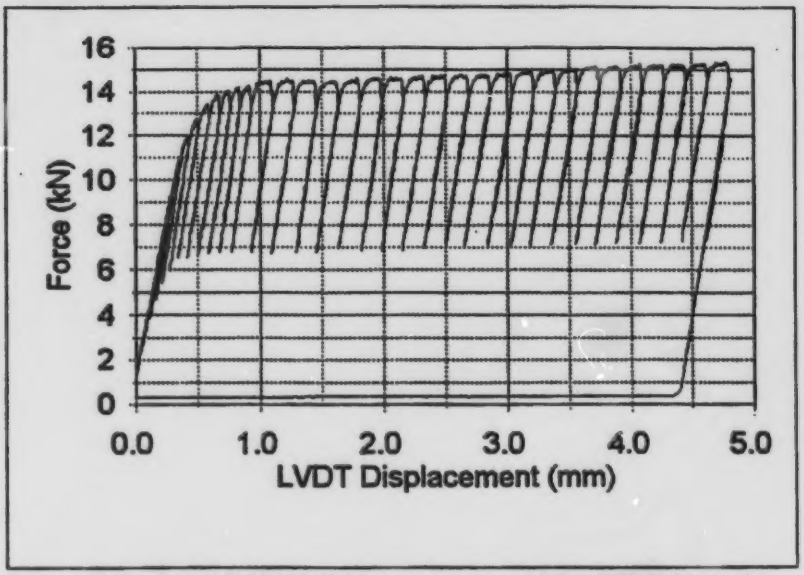

Figure D.3 - Load/LVDT displacement record for 350 WT steel specimen #108 at -95°C.

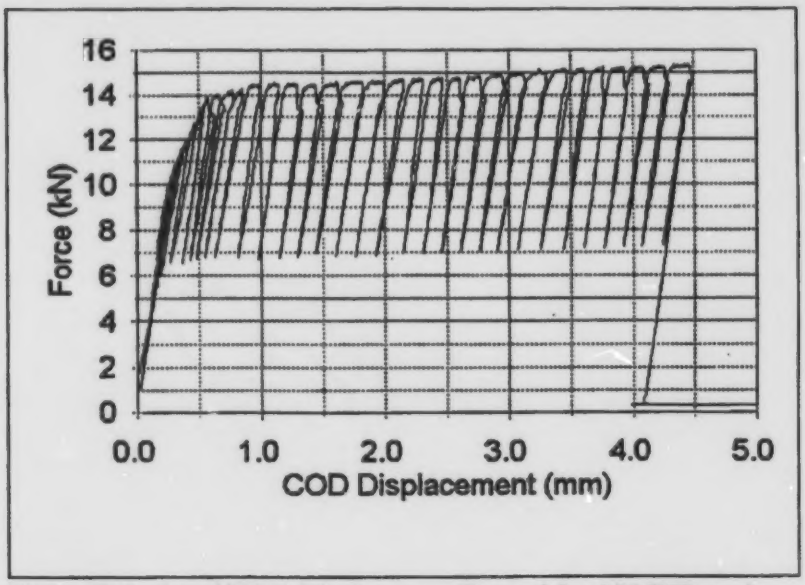

Figure D.4 - Load/COD Displacement Record for 350 WT steel specimen #108 at -95°C.

Appendix E - Data Records for 8 mm 350 WT Steel (T-L Orientation)

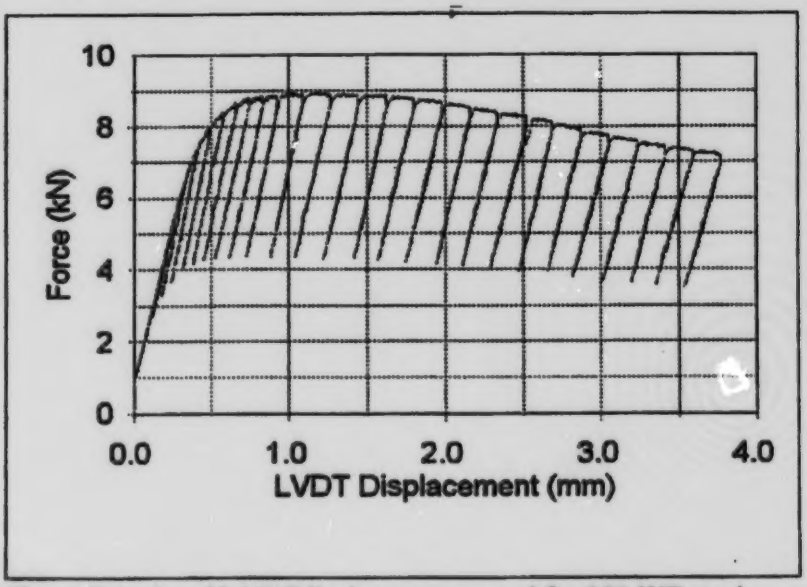

Figure E.1 - Load/LVDTdisplacement record for 350 WT steel specimen #97 at -10°C.

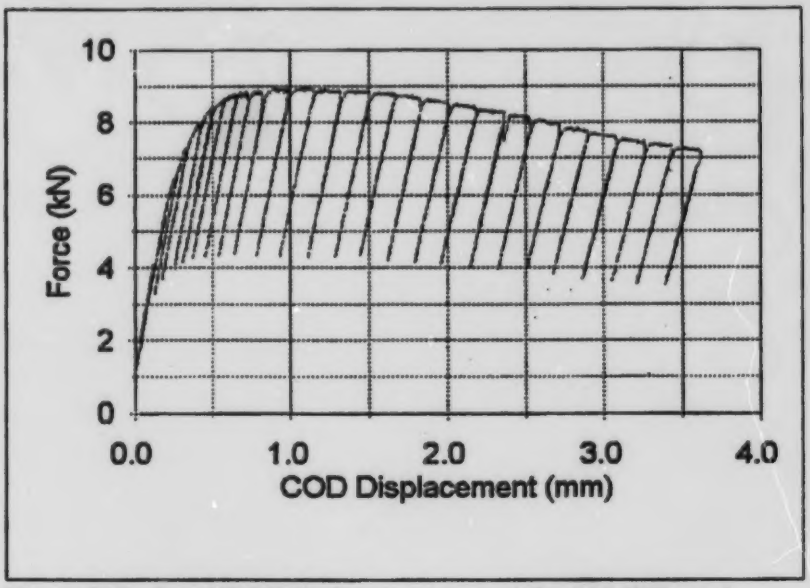

Figure E.2 - Load/CODdisplacement record for 350 WT steel specimen #97 at -10°C.

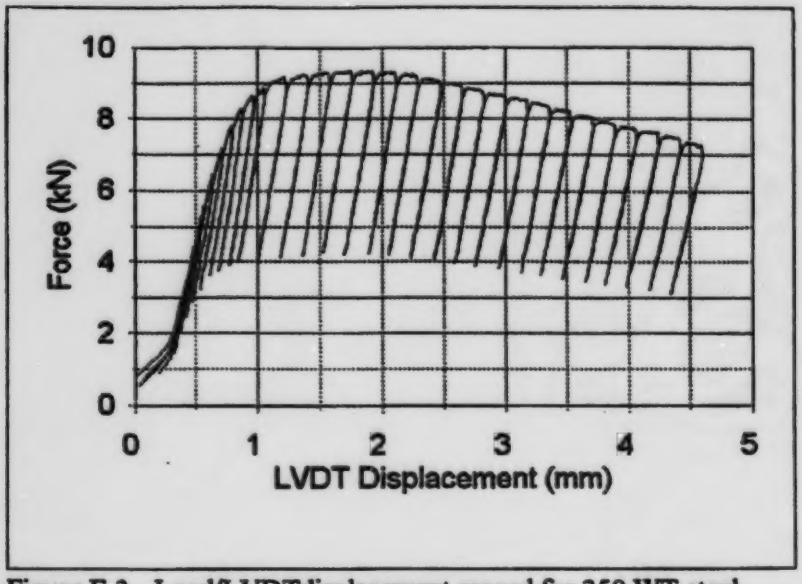

Figure E.3 - Load/LVDTdisplacement record for 350 WT steel specimen #93 at -25°C.

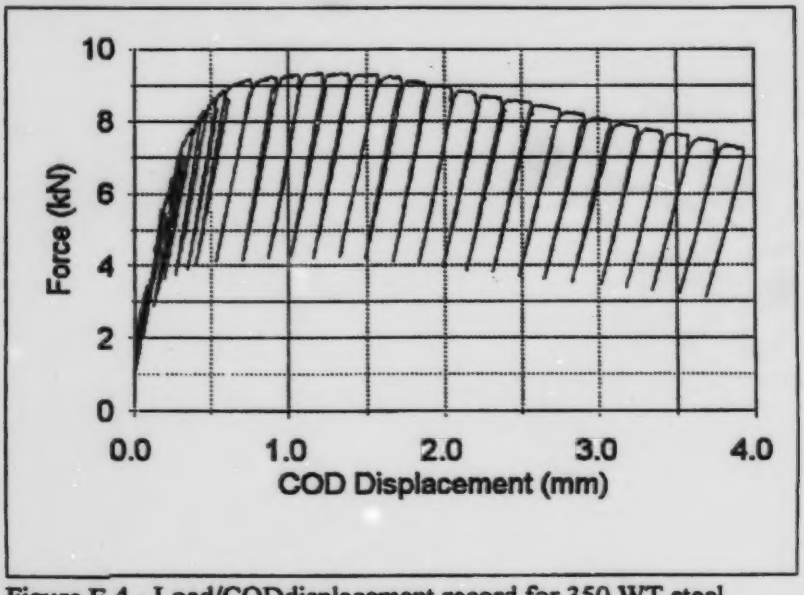

Figure E.4 - Load/CODdisplacement record for 350 WT steel specimen #93 at -25°C.

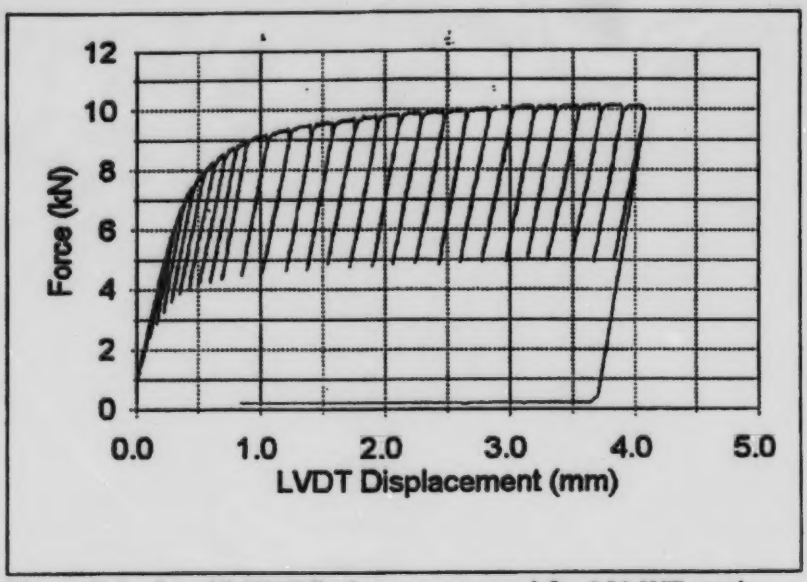

Figure E.5 - Load/LVDTdisplacement record for 350 WT steel specimen #94 at -35°C.

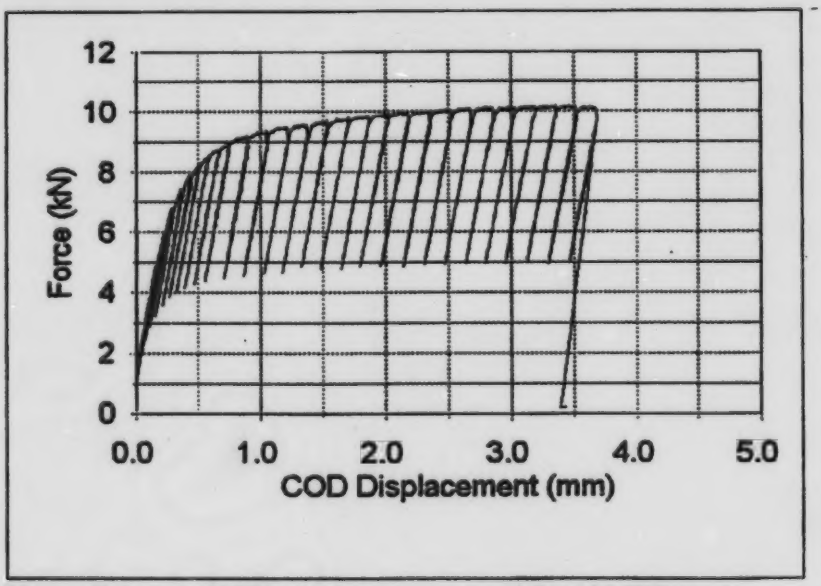

Figure E.6 - Load/CODdisplacement record for 350 WT steel specimen #94 at -35°C.

Appendix F - Data Records for 8 mm 350 WT Steel (L-T Orientation)

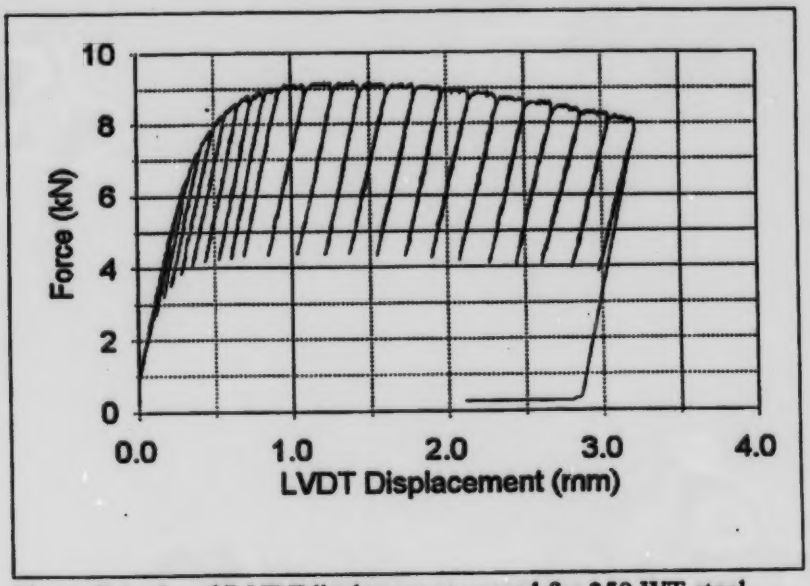

Figure F.1 - Load/LVDTdisplacement record for 350 WT steel specimen #90 at -35°C.

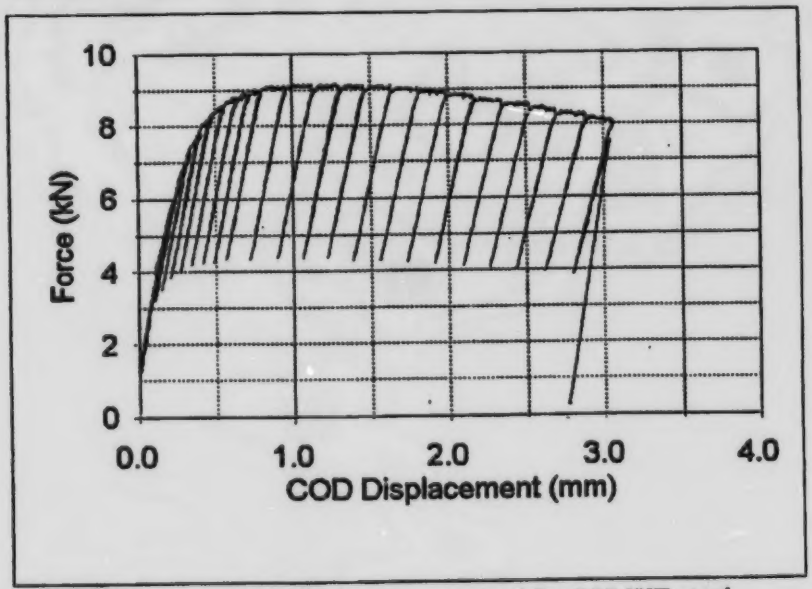

Figure F.2 - Load/CODdisplacement record for 350 WT steel specimen #90 at -35°C.

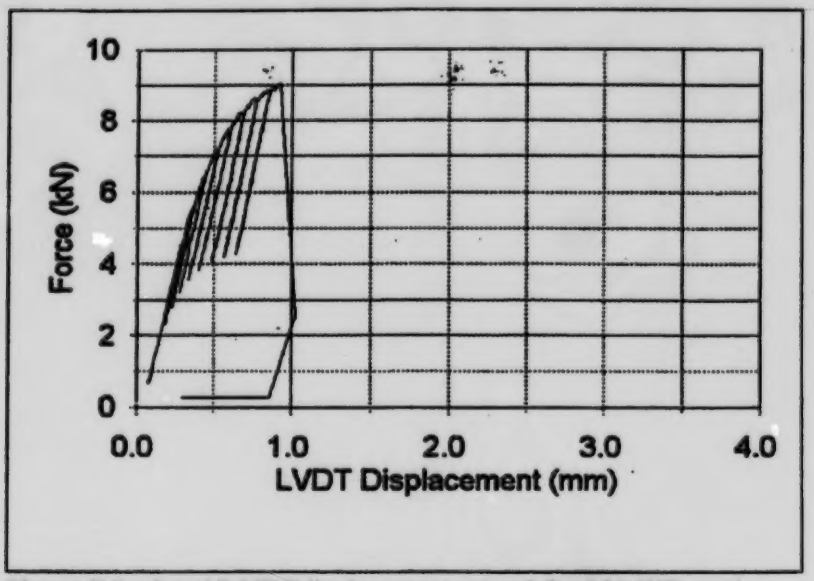

Figure F.3 - Load/LVDTdisplacement record for 350 WT steel specimen #91 at -50°C.

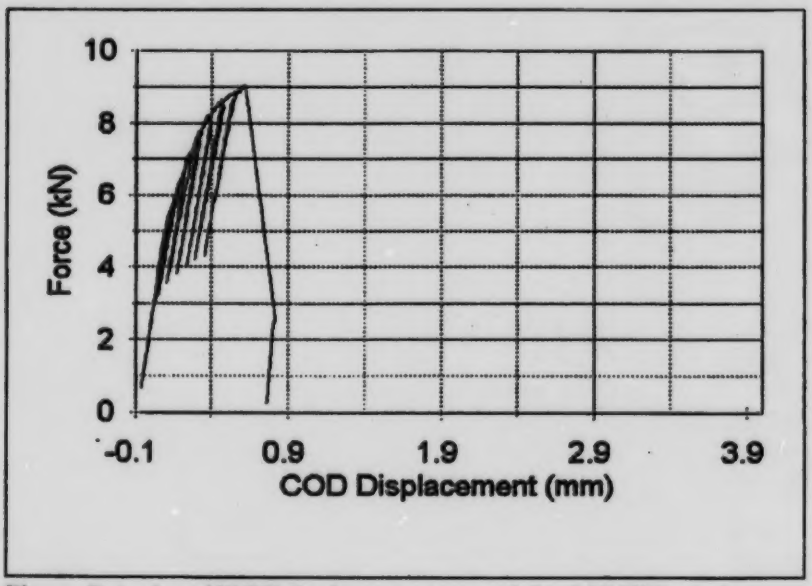

Figure F.4 - Load/CODdisplacement record for 350 WT steel specimen #91 at -50°C.

Appendix G - Data Records for ASTM A517 Steel (T-L Orientation)

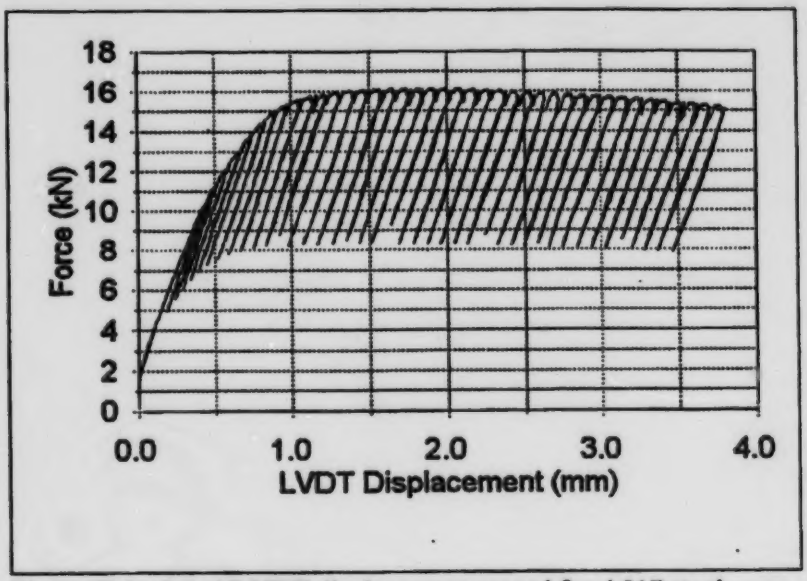

Figure G.1 - Load/LVDT displacement record for A517 steel specimen #84 at -45°C.

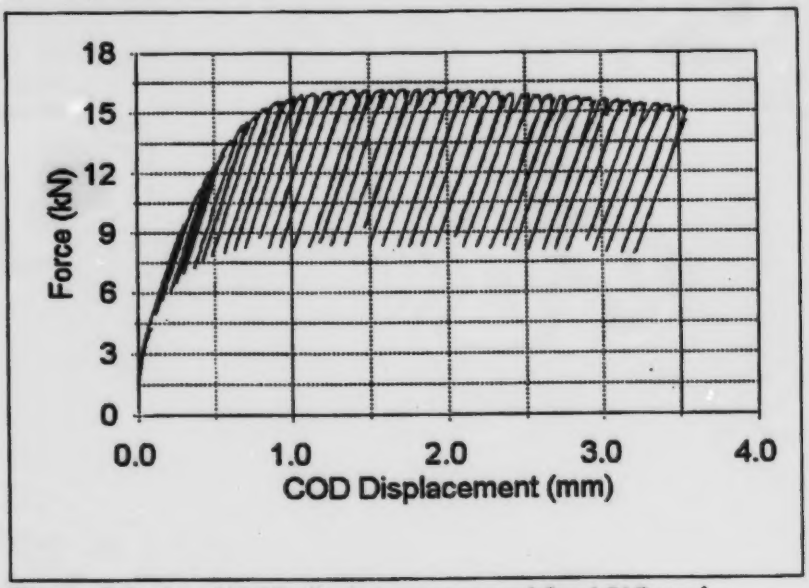

Figure G.2 - Load/COD displacement record for A517 steel specimen #84 at -45°C.

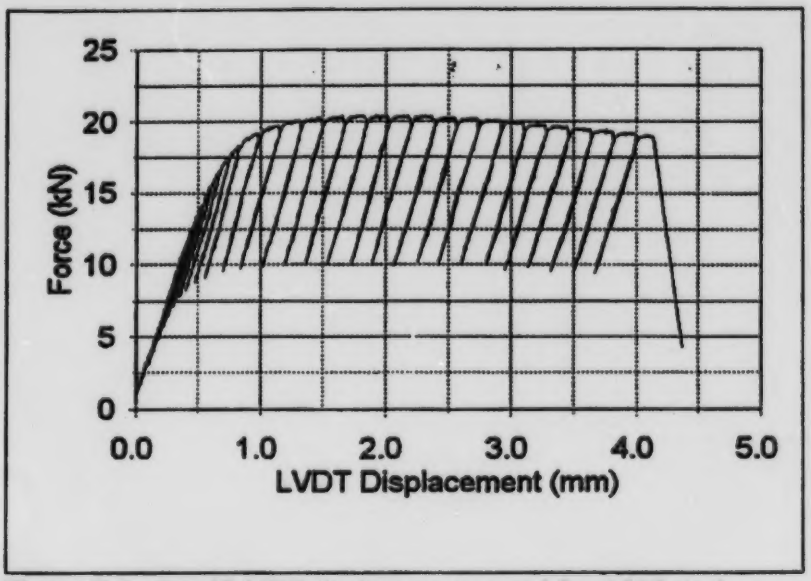

Figure G.3 - Load/LVDT displacement record for A517 steel specimen #110 at -75°C.

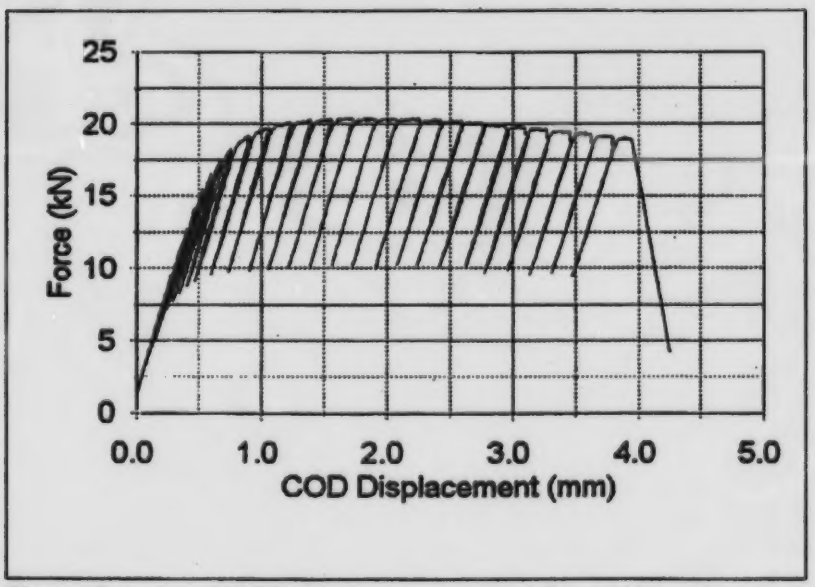

Figure G.4 - Load/COD displacement record for A517 steel specimen #110 at -75°C.

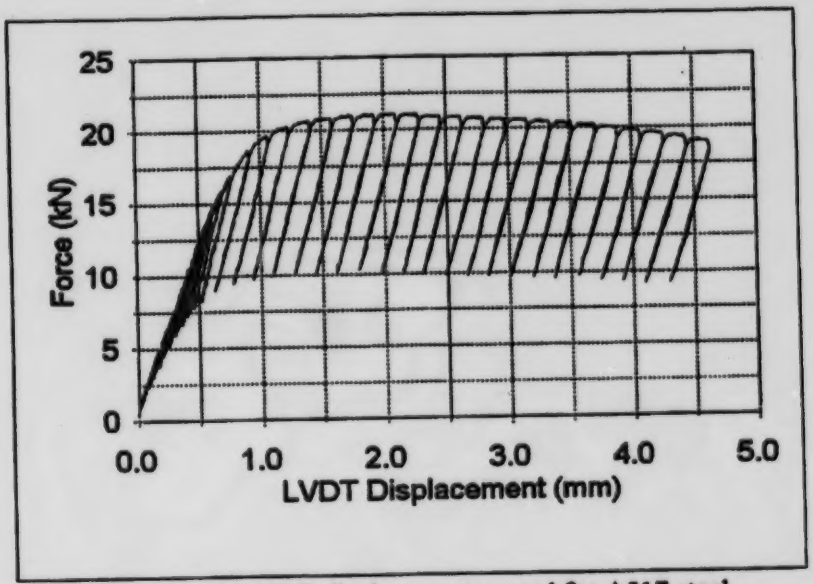

Figure G.5 - Load/LVDT displacement record for A517 steel specimen #105 at -95°C.

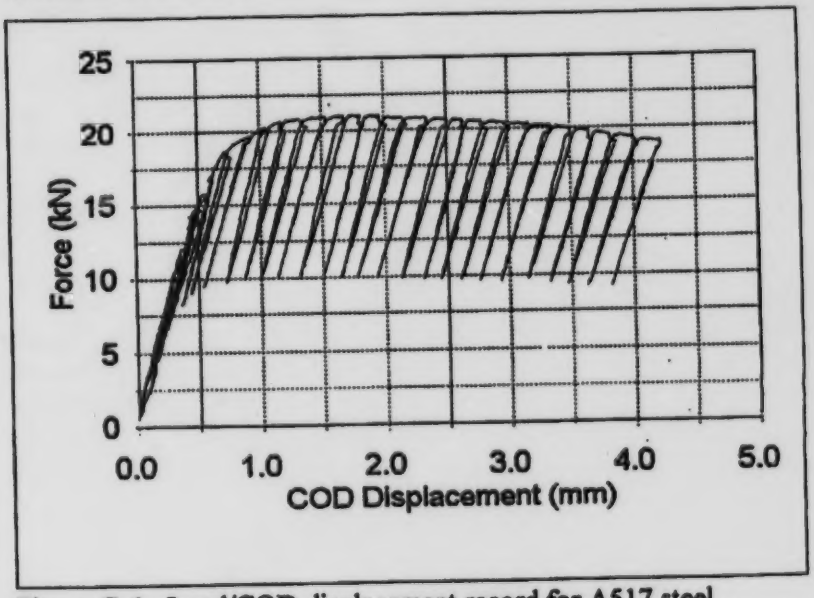

Figure G.6 - Load/COD displacement record for A517 steel specimen #105 at -95°C.

Appendix H - Data Records for ASTM A517 steel (L-T Orientation)

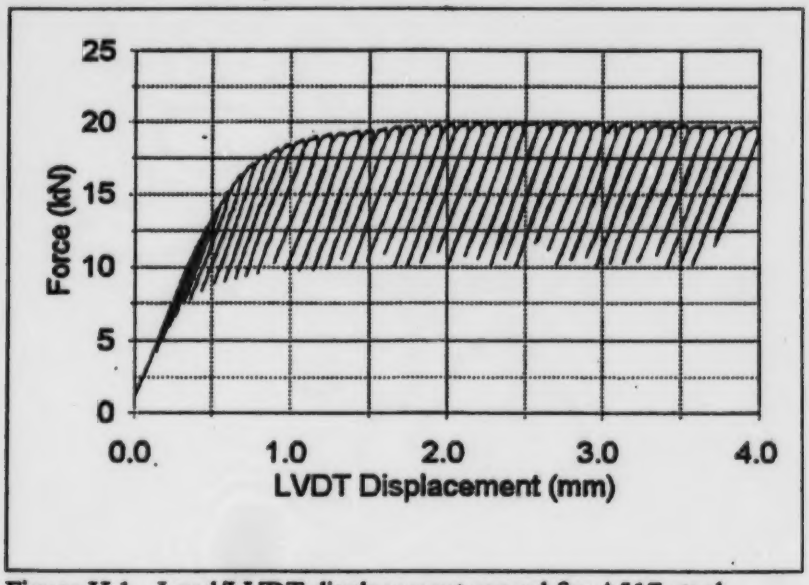

Figure H.1 - Load/LVDT displacement record for A517 steel specimen #83 at -55°C.

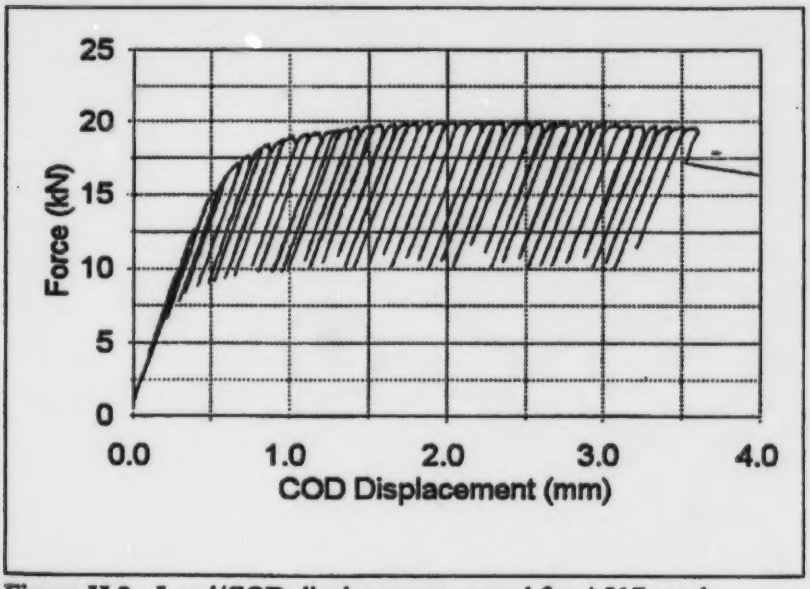

Figure H.2 - Load/COD displacement record for A517 steel specimen #83 at -55°C.

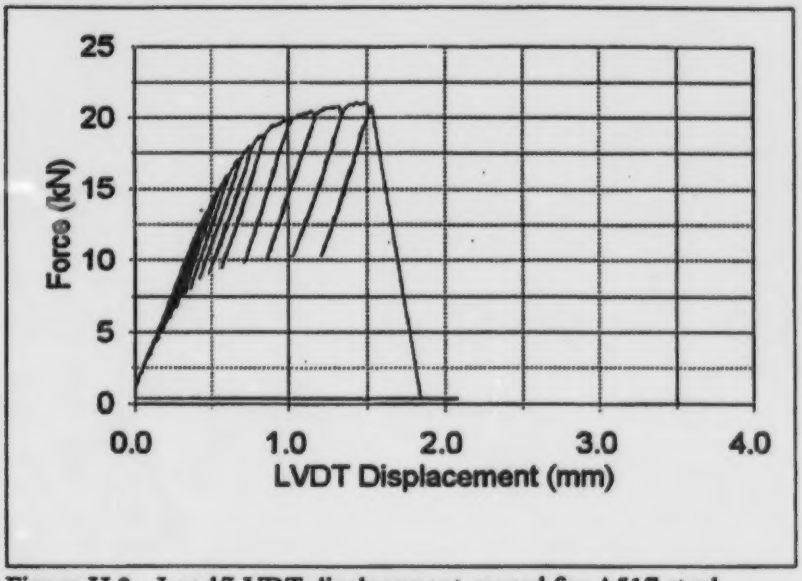

Figure H.3 - Load/LVDT displacement record for A517 steel specimen #109 at -95°C.

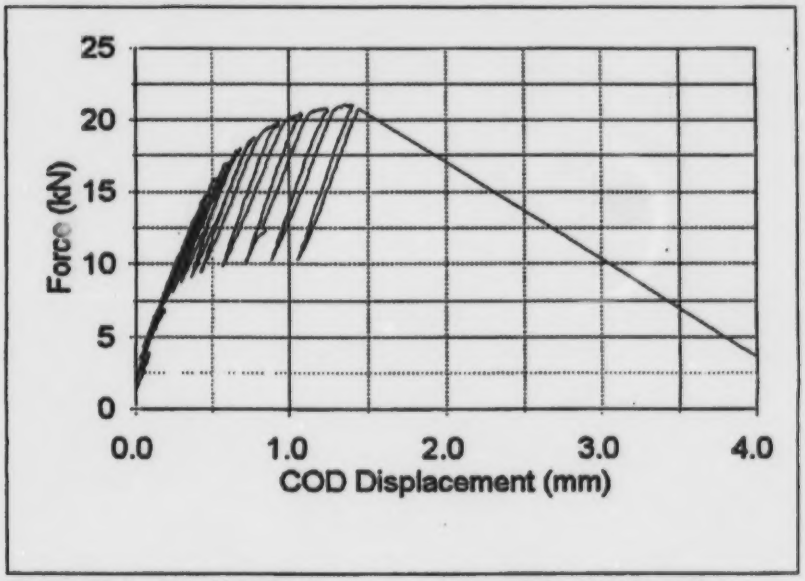

Figure H.4 - Load/COD displacement record for A517 steel specimen #109 at -95°C.

Appendix I - Data Records for Various Steel Weldments

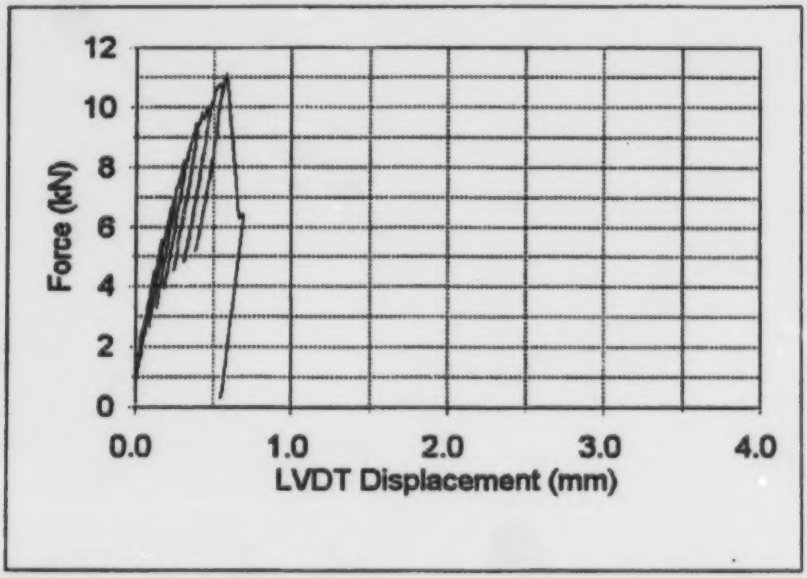

Figure I.1 - Load/LVDT displacement record for weldment 12B specimen #104 at -40°C.

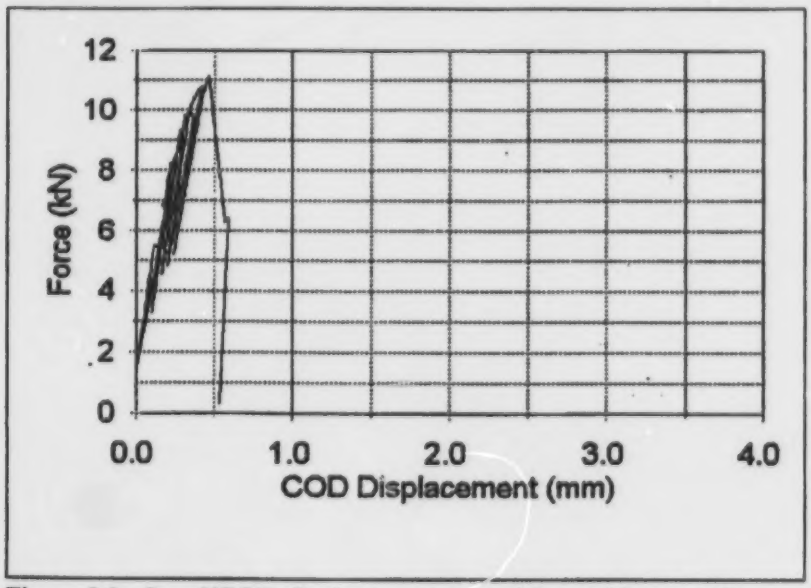

Figure I.2 - Load/COD displacement record for weldment 12B specimen #104 at -40°C.

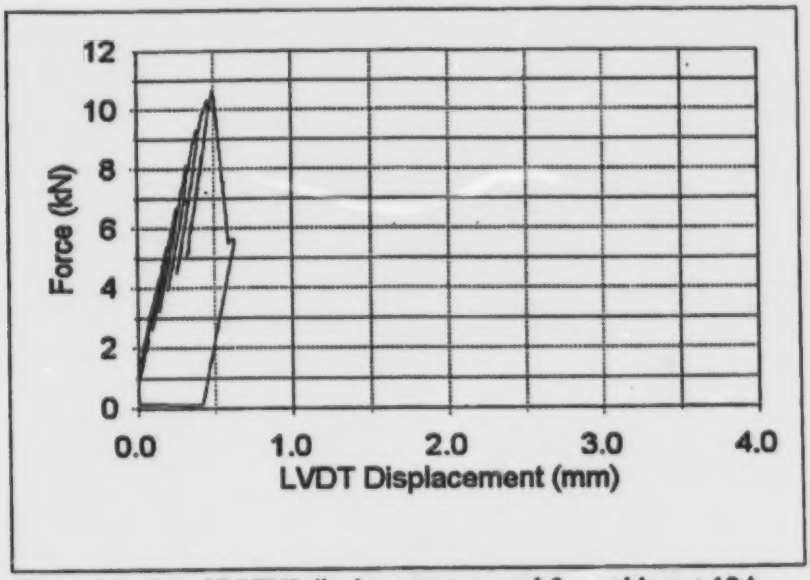

Figure I.3 - Load/LVDT displacement record for weldment 12A specimen #82 at -50°C.

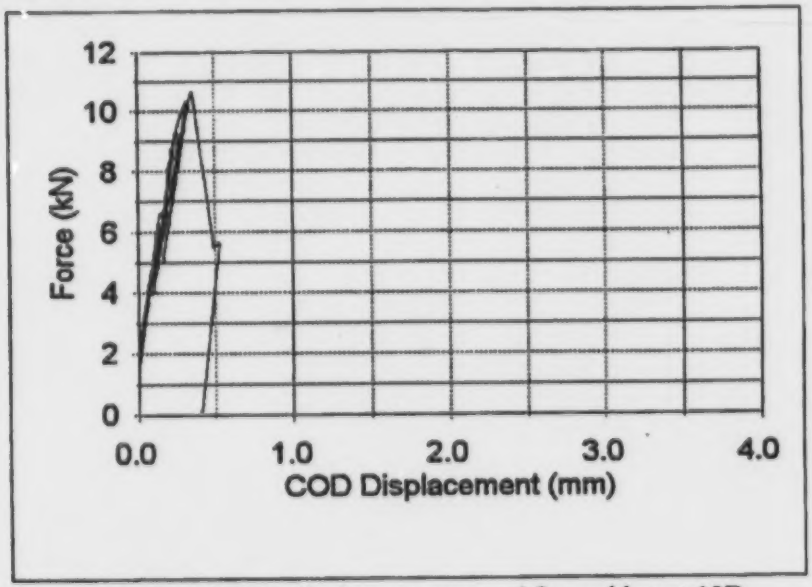

Figure I.4 - Load/COD displacement record for weldment 12B specimen #82 at -50°C.

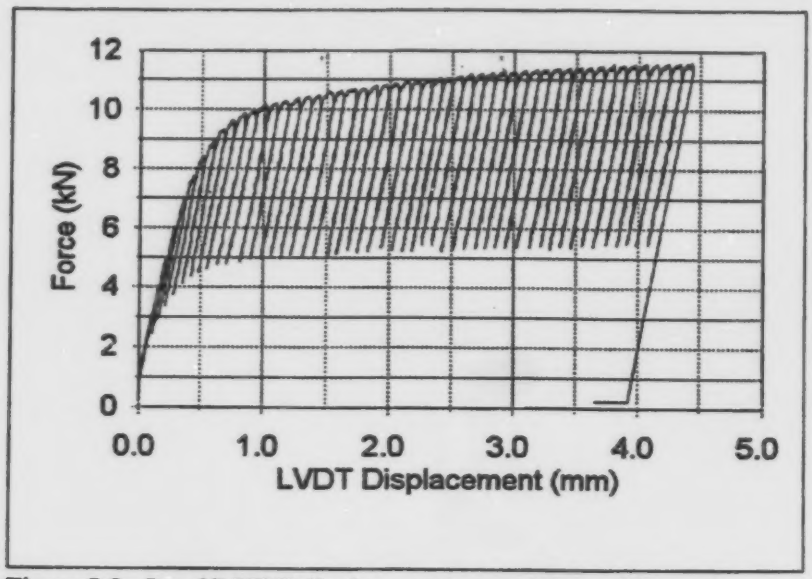

Figure I.5 - Load/LVDT displacement record for weldment 3 specimen #85 at -50°C.

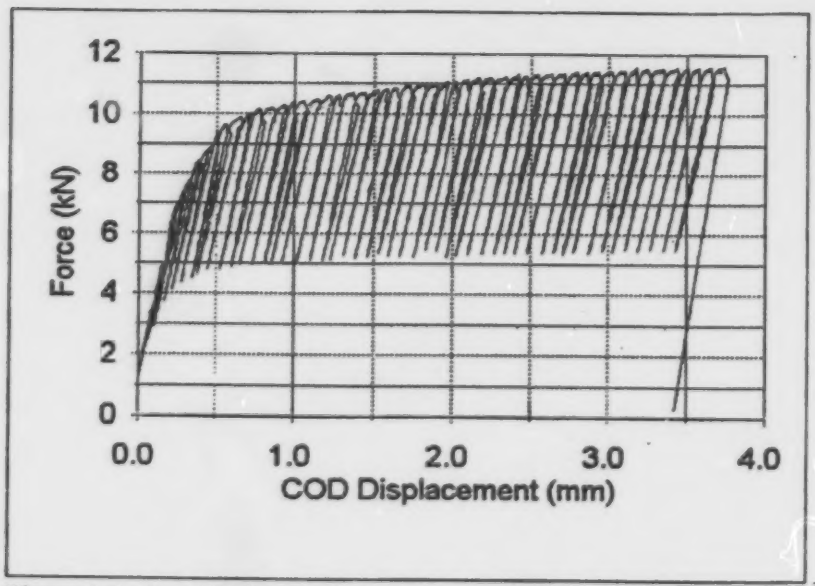

Figure I.6 - Load/COD displacement record for weldment 3 specimen #85 at -50°C.

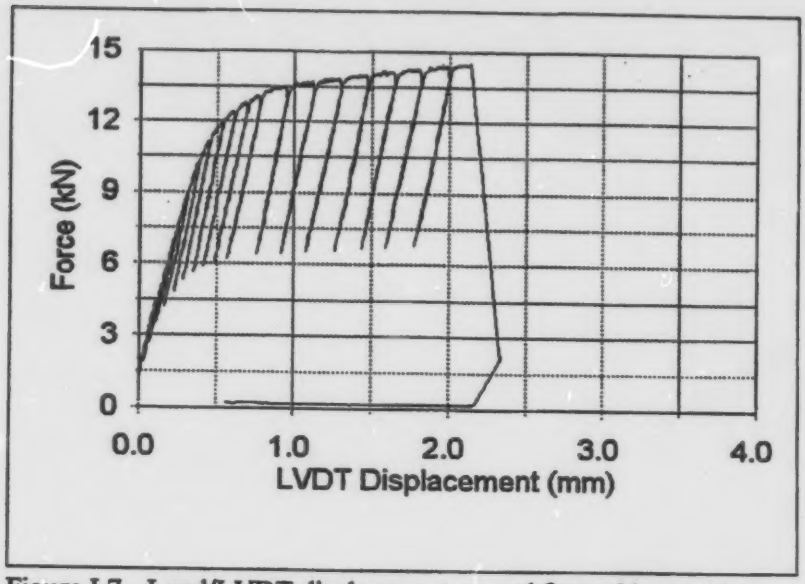

Figure I.7 - Load/LVDT displacement record for weldment 11 specimen #87 at -50°C.

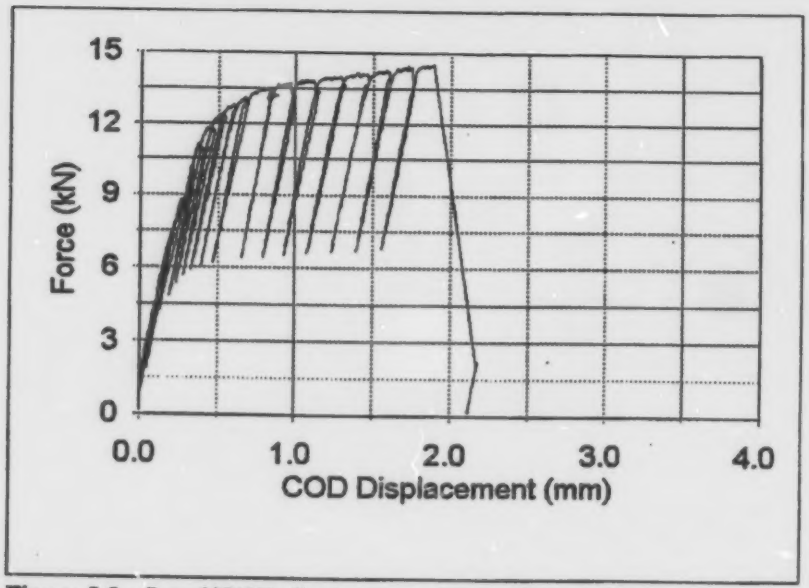

Figure I.8 - Load/COD displacement record for weldment 11 specimen #87 at -50°C.

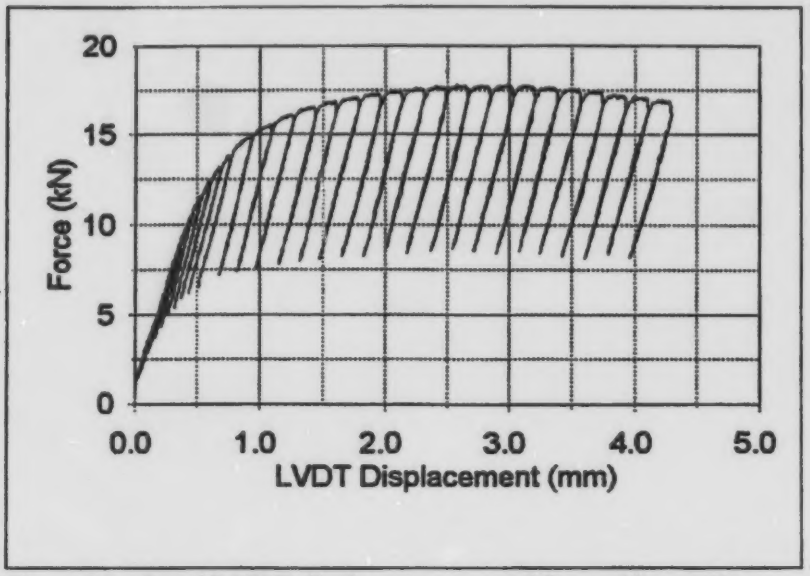

Figure I.9 - Load/LVDT displacement record for weldment 20 specimen #86 at -40°C.

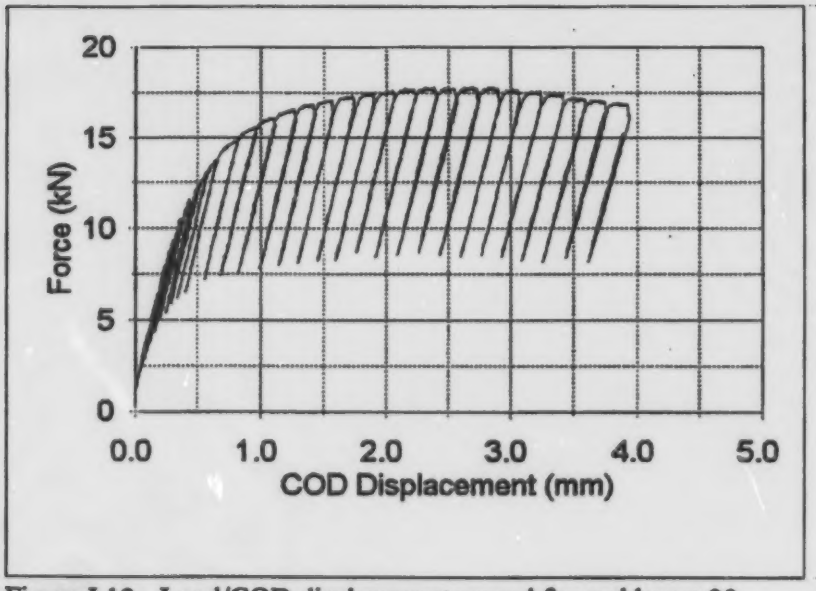

Figure I.10 - Load/COD displacement record for weldment 20 specimen #86 at -40°C.

Appendix J - ASTM E-399 Results for Lloyds Grade A Steel

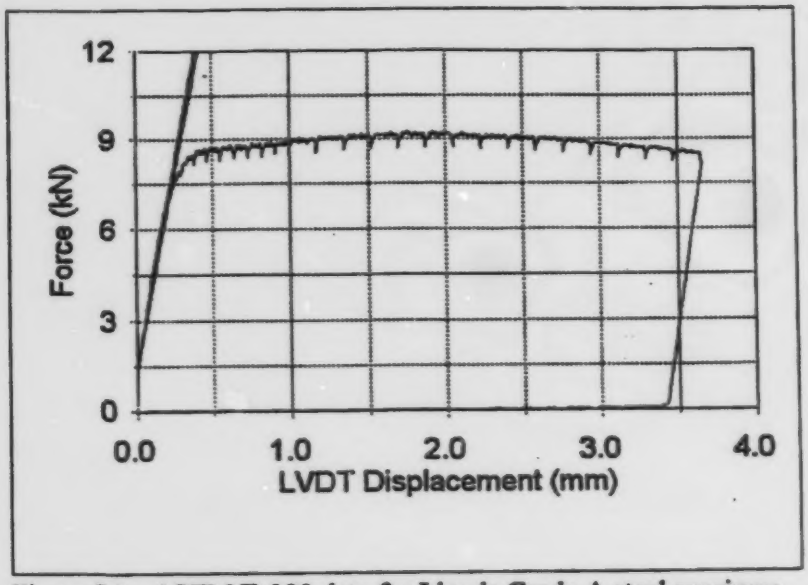

Figure J.1 - ASTM E-399 data for Lloyds Grade A steel specimen #100 at 22 °C.

TEST RESULTS

Specimen Identification: Specimen-8005-100
Material Type: Lloyds_GradeA_TL_B21
Material Yield: 350 Mpa

Specimen Width: 40.70 mm
Specimen Thickness: 12.49 mm
Specimen Span: 163.00 mm
Initial Specimen Compliance 27.25 mm/kN
Initial Crack Length Readings 23.69 mm 24.18 mm 23.92 mm
Average Crack Length 23.93 mm 0.587961 a/W Valid

Fracture Toughness Kq: 39.73 Mpa sqrt(m)

Validation Criteria
Pmax 9.08 Pq 6.94 Pmax/Pq 1.31 Invalid
Through Thickness Constraint Invalid 12.49 < 12.882339
Remaining Ligament Constraint Valid 16.77 > 12.882339

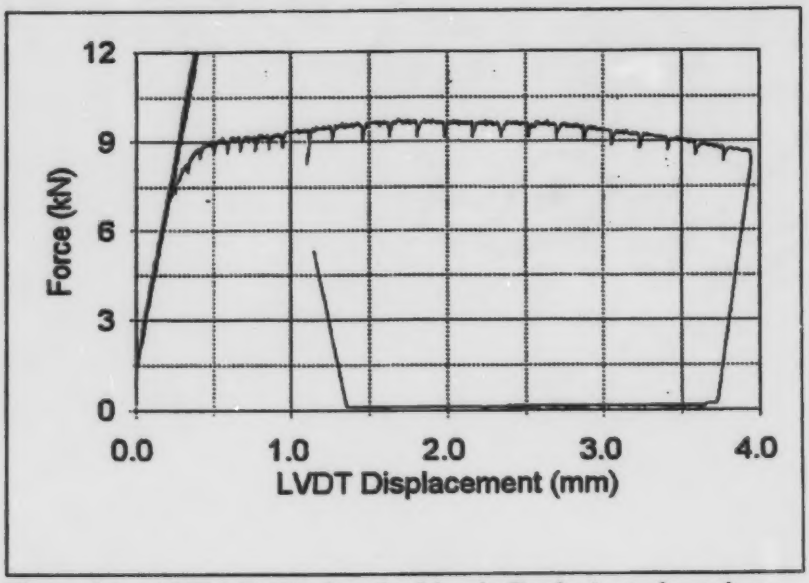

Figure J.2 - ASTM E-399 data for Lloyds Grade A steel specimen #99 at 0 °C.

TEST RESULTS

Specimen Identification: Specimen-8005-99
Material Type: Lloyds_GradeA_TL_B30
Material Yield: 350 Mpa

Specimen Dimensions

Specimen Width: 40.69 mm
Specimen Thickness: 12.60 mm
Specimen Span: 163.00 mm
Initial Specimen Compliance 28.49 mm/kN
Initial Crack Length Readings 23.72 mm 23.85 mm 23.66 mm
Average Crack Length 23.74 mm 0.583518 a/W Valid

Fracture Toughness Kq: 41.40 Mpa sqrt(m)

Validation Criteria
Pmax 9.50 Pq 7.41 Pmax/Pq 1.28 Invalid
Through Thickness Constraint Invalid 12.60 < 13.989669
Remaining Ligament Constraint Valid 16.95 > 13.989669

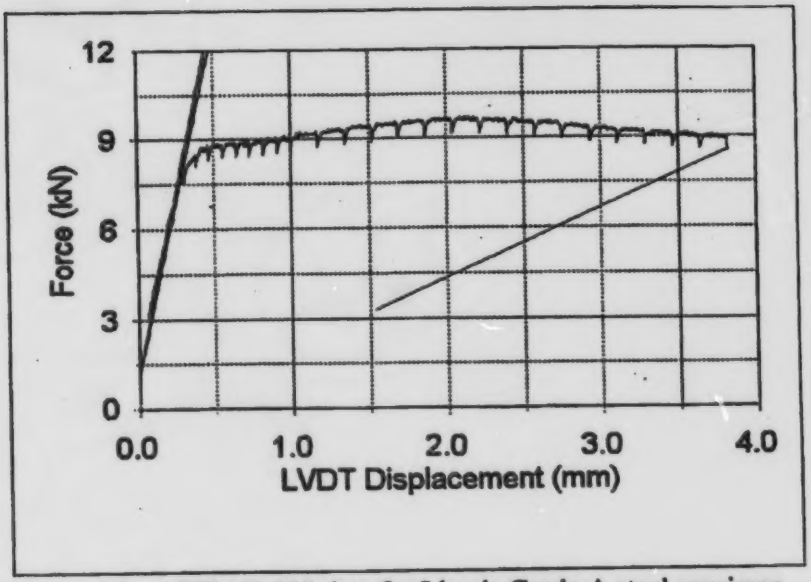

Figure J.3 - ASTM E-399 data for Lloyds Grade A steel specimen #96 at -22 °C, T-L orientation.

TEST RESULTS

Specimen Identification: Specimen-8005-96
Material Type: Lloyds_GradeA_TL_B40
Material Yield: 350 Mpa

Specimen Dimensions

Specimen Width: 40.62 mm
Specimen Thickness: 12.46 mm
Specimen Span: 163.00 mm
Initial Specimen Compliance 24.35 mm/kN
Initial Crack Length Readings 23.83 mm 24.06 mm 23.77 mm
Average Crack Length 23.89 mm 0.588052 a/W Valid

Fracture Toughness Kq: 44.23 Mpa sqrt(m)

Validation Criteria
Pmax 9.48 Pq 7.68 Pmax/Pq 1.23 Invalid
Through Thickness Constraint Invalid 12.46 < 15.969316
Remaining Ligament Constraint Valid 16.73 > 15.969316

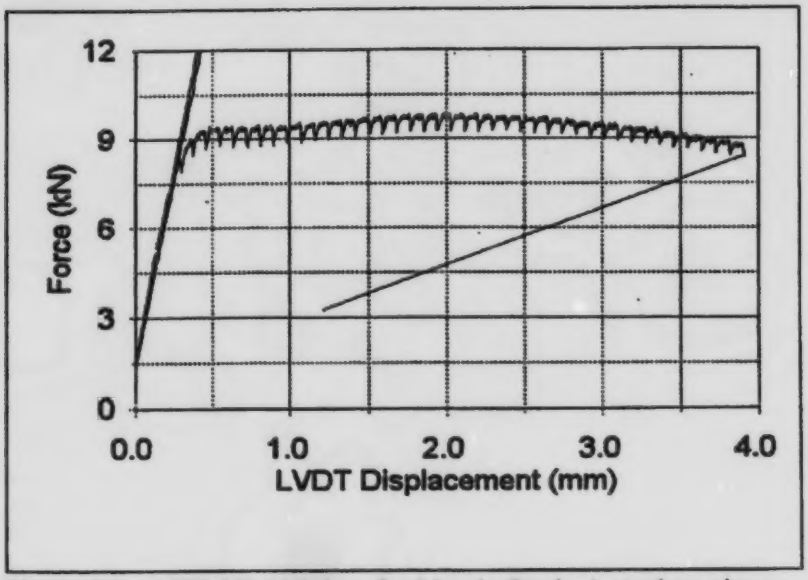

Figure J.4 - ASTM E-399 data for Lloyds Grade A steel specimen #81 at -40 °C, T-L orientation.

TEST RESULTS

Specimen Identification. Specimen-8005-81
Material Type: Lloyds_GradeA_TL_B31
Material Yield: 350 Mpa

Specimen Dimensions

Specimen Width: 40.71 mm
Specimen Thickness: 12.51 mm
Specimen Span: 163.00 mm
Initial Specimen Compliance 26.57 mm/kN
Initial Crack Length Readings 24.14 mm 24.34 mm 23.92 mm
Average Crack Length 24.13 mm 0.592811 a/W Valid

Fracture Toughness Kq: 47.32 Mpa sqrt(m)

Validation Criteria
Pmax 9.66 Pq 8.13 Pmax/Pq 1.19 Invalid
Through Thickness Constraint Invalid 12.51 < 18.278938
Remaining Ligament Constraint Invalid 16.58 < 18.278938

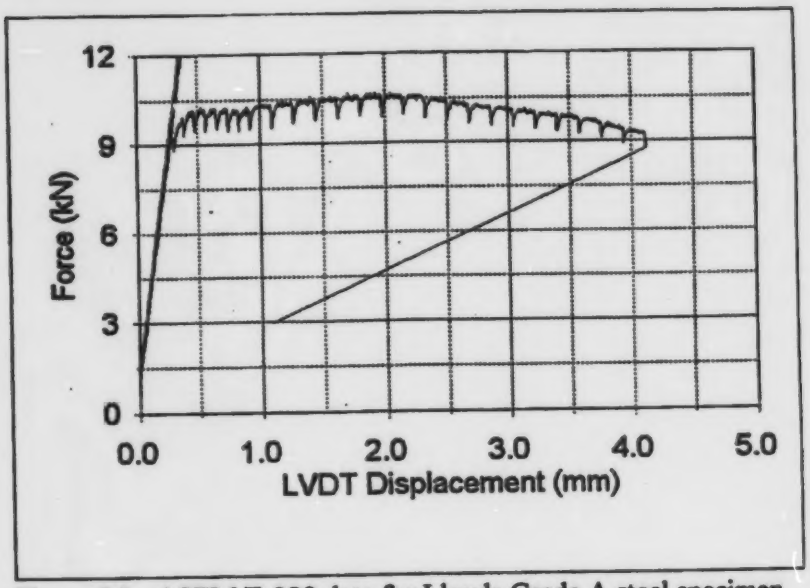

Figure J.5 - ASTM E-399 data for Lloyds Grade A steel specimen #102 at -55 °C, T-L orientation.

TEST RESULTS

Specimen Identification: Specimen-8005-102
Material Type: Lloyds_GradeA_TL_B22
Material Yield: 350 Mpa

Specimen Dimensions

Specimen Width: 40.74 mm
Specimen Thickness: 12.45 mm
Specimen Span: 163.00 mm
Initial Specimen Compliance 30.57 mm/kN
Initial Crack Length Readings 23.54 mm 23.79 mm 23.48 mm
Average Crack Length 23.60 mm 0.579365 a/W Valid

Fracture Toughness Kq: 50.70 Mpa sqrt(m)

Validation Criteria
Pmax 10.43 Pq 9.12 Pmax/Pq 1.14 Invalid
Through Thickness Constraint Invalid 12.45 < 20.984211
Remaining Ligament Constraint Invalid 17.14 < 20.984211

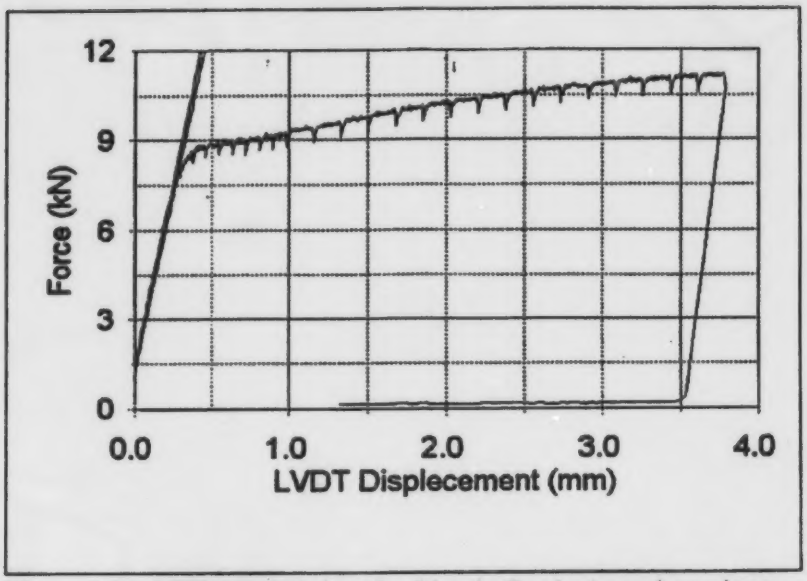

Figure J.6 - ASTM E-399 data for Lloyds Grade A steel specimen #98 at -0 °C, L-T orientation.

TEST RESULTS

Specimen Identification: Specimen-8005-98
Material Type: Lloyds_GradeA_LT_B8
Material Yield: 350 Mpa

Specimen Dimensions

Specimen Width: 40.64 mm
Specimen Thickness: 12.46 mm
Specimen Span: 163.00 mm
Initial Specimen Compliance 25.31 mm/kN
Initial Crack Length Readings 23.71 mm 24.10 mm 23.82 mm
Average Crack Length 23.88 mm 0.587516 a/W Valid

Fracture Toughness Kq: 45.32 Mpa sqrt(m)

Validation Criteria
Pmax 11.00 Pq 7.89 Pmax/Pq 1.39 Invalid
Through Thickness Constraint Invalid 12.46 < 16.765993
Remaining Ligament Constraint Invalid 16.76 < 16.765993

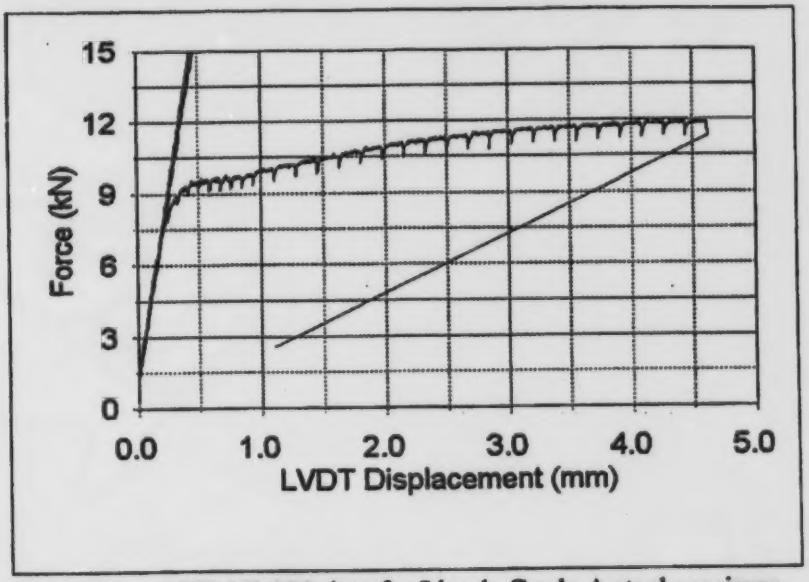

Figure J.7 - ASTM E-399 data for Lloyds Grade A steel specimen #95 at -20 °C, L-T orientation.

TEST RESULTS

Specimen Identification: Specimen-8005-95
Material Type: Lloyds_GradeA_LT_NM
Material Yield: 350 Mpa

Specimen Dimensions

Specimen Width: 40.41 mm
Specimen Thickness: 12.53 mm
Specimen Span: 163.00 mm
Initial Specimen Compliance 31.57 mm/kN
Initial Crack Length Readings 23.03 mm 23.45 mm 23.34 mm
Average Crack Length 23.27 mm 0.575930 a/W Valid

Fracture Toughness Kq: 44.18 Mpa sqrt(m)

Validation Criteria
Pmax 11.75 Pq 8.01 Pmax/Pq 1.47 Invalid
Through Thickness Constraint Invalid 12.53 < 15.932611
Remaining Ligament Constraint Valid 17.14 > 15.932611

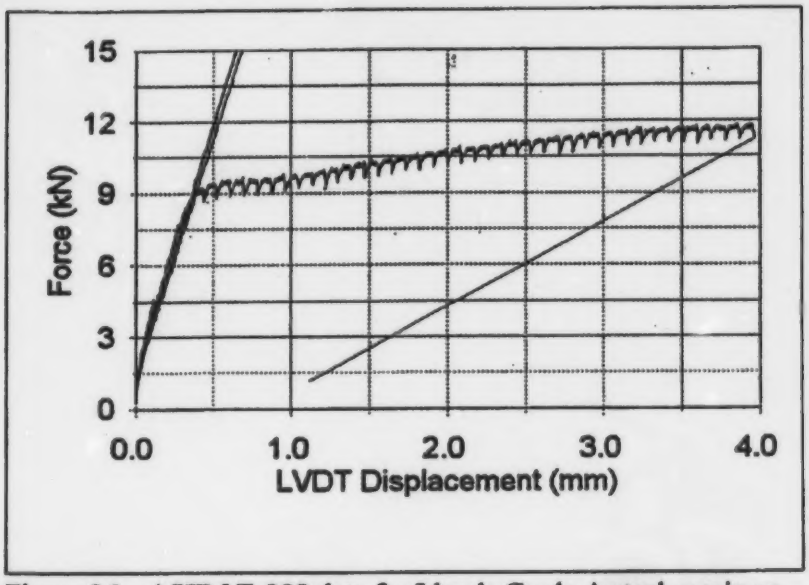

Figure J.8 - ASTM E-399 data for Lloyds Grade A steel specimen #80 at -40 °C, L-T orientation.

TEST RESULTS

Specimen Identification: Specimen-8005-80
Material Type: Lloyds_GradeA_LT_B12
Material Yield: 350 Mpa

Specimen Dimensions

Specimen Width: 40.71 mm
Specimen Thickness: 12.50 mm
Specimen Span: 163.00 mm
Initial Specimen Compliance 21.30 mm/kN
Initial Crack Length Readings 23.46 mm 23.88 mm 23.76 mm
Average Crack Length 23.70 mm 0.582167 a/W Valid

Fracture Toughness Kq: 50.11 Mpa sqrt(m)

Validation Criteria
Pmax 11.56 Pq 8.95 Pmax/Pq 1.29 Invalid
Through Thickness Constraint Invalid 12.50 < 20.497921
Remaining Ligament Constraint Invalid 17.01 < 20.497921

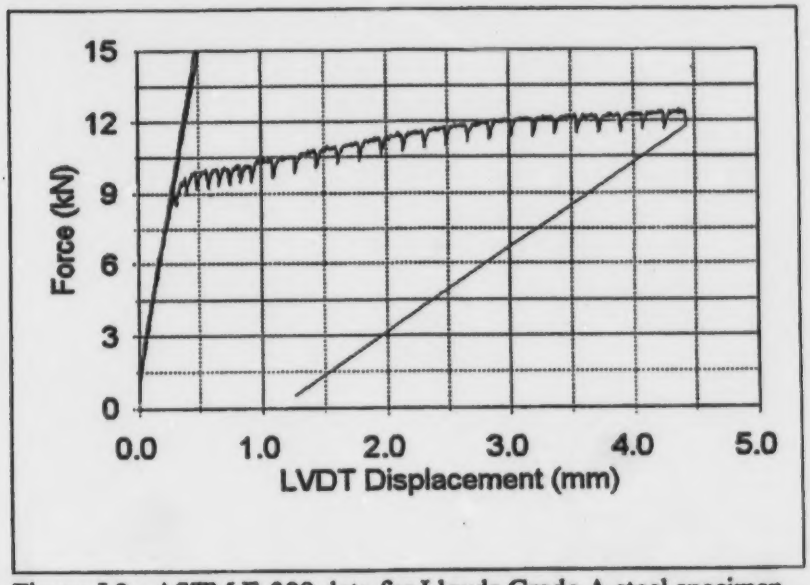

Figure J.9 - ASTM E-399 data for Lloyds Grade A steel specimen #101 at -55 °C, L-T orientation.

TEST RESULTS

Specimen Identification: Specimen-8005-101
Material Type: Lloyds_GradeA_LT_B10
Material Yield: 350 Mpa

Specimen Dimensions

Specimen Width: 40.67 mm
Specimen Thickness: 12.47 mm
Specimen Span: 163.00 mm
Initial Specimen Compliance 29.27 mm/kN
Initial Crack Length Readings 23.78 mm 24.04 mm 23.41 mm
Average Crack Length 23.74 mm 0.583805 a/W Valid

Fracture Toughness Kq: 43.39 Mpa sqrt(m)

Validation Criteria
Pmax 12.17 Pq 7.68 Pmax/Pq 1.59 Invalid
Through Thickness Constraint Invalid 12.47 < 15.371145
Remaining Ligament Constraint Valid 16.93 > 15.371145

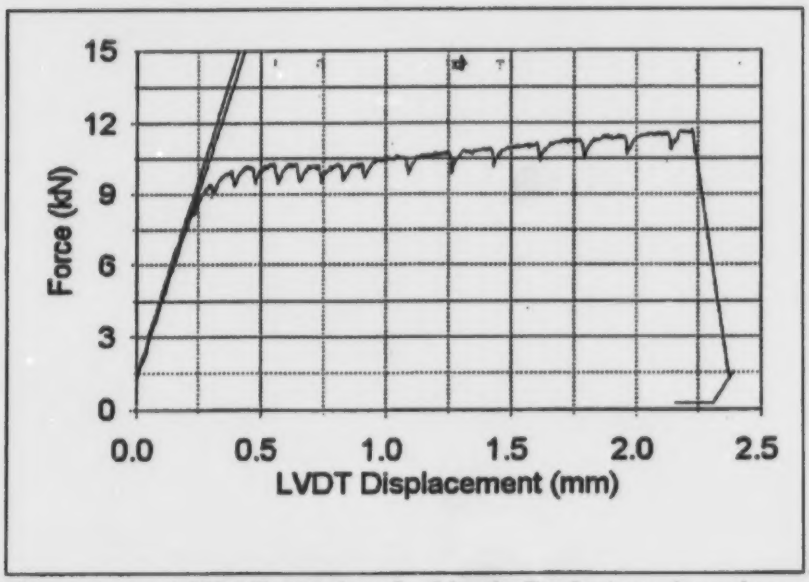

Figure J.10 - ASTM E-399 data for Lloyds Grade A steel specimen #103 at -70 °C, L-T orientation.

TEST RESULTS

Specimen Identification: Specimen-8005-103
Material Type: Lloyds_GradeA_LT_B11
Material Yield: 350 Mpa

Specimen Dimensions

Specimen Width: 40.74 mm
Specimen Thickness: 12.51 mm
Specimen Span: 163.00 mm
Initial Specimen Compliance 33.21 mm/kN
Initial Crack Length Readings 23.58 mm 24.12 mm 23.85 mm
Average Crack Length 23.85 mm 0.585420 a/W Valid

Fracture Toughness Kq: 46.31 Mpa sqrt(m)

Validation Criteria
Pmax 11.35 Pq 8.19 Pmax/Pq 1.39 Invalid
Through Thickness Constraint Invalid 12.51 < 17.508125
Remaining Ligament Constraint Invalid 16.89 < 17.508125

Appendix K - ASTM E-399 Results for 12mm 350WT Plate

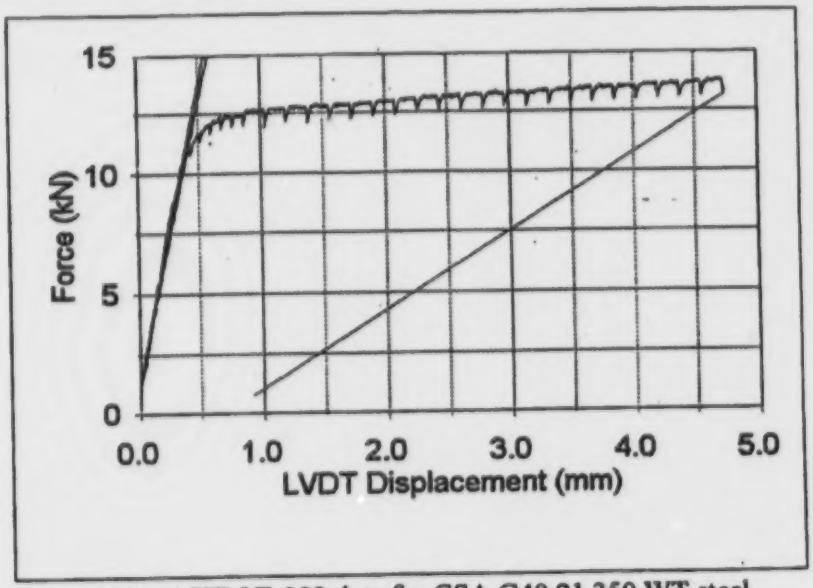

Figure K.1 - ASTM E-399 data for CSA G40.21 350 WT steel specimen #88 at -45 °C, T-L orientation.

TEST RESULTS

Specimen Identification: Specimen-8005-88
Material Type: 12mm_350WT_TLC
Material Yield: 350 Mpa

Specimen Width: 40.61 mm
Specimen Thickness: 11.87 mm
Specimen Span: 163.00 mm
Initial Specimen Compliance 25.08 mm/kN
Initial Crack Length Readings 23.18 mm 23.80 mm 23.93 mm
Average Crack Length 23.64 mm 0.582041 a/W Valid

Fracture Toughness Kq: 64.28 Mpa sqrt(m)

Validation Criteria
Pmax 13.57 Pq 10.87 Pmax/Pq 1.25 Invalid
Through Thickness Constraint Invalid 11.87 < 33.732738
Remaining Ligament Constraint Invalid 16.97 < 33.732738

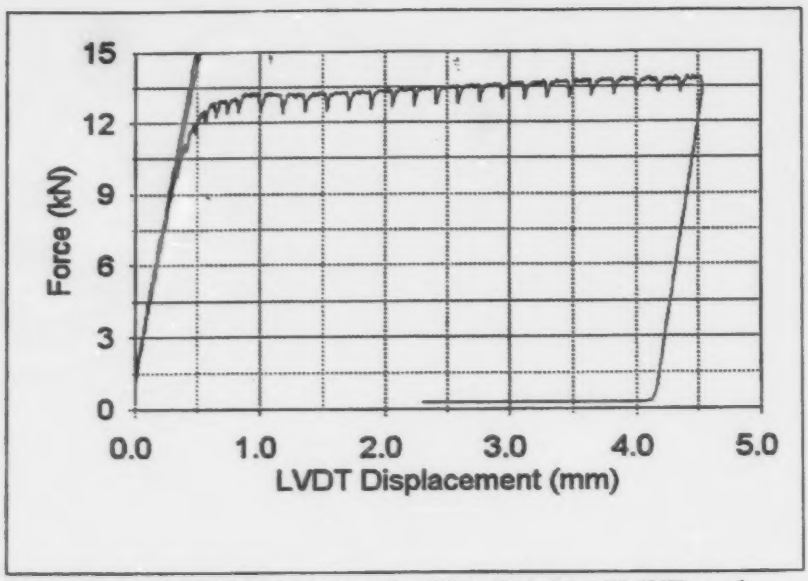

Figure K.2 - ASTM E-399 data for CSA G40.21 350 WT steel specimen #92 at -65 °C, T-L orientation.

TEST RESULTS

Specimen Identification: Specimen-8005-92
Material Type: 12mm_350WT_TLB
Material Yield: 350 Mpa

Specimen Dimensions

Specimen Width: 40.57 mm
Specimen Thickness: 11.92 mm
Specimen Span: 163.00 mm
Initial Specimen Compliance 27.94 mm/kN
Initial Crack Length Readings 23.15 mm 23.89 mm 23.98 mm
Average Crack Length 23.67 mm 0.583518 a/W Valid

Fracture Toughness Kq: 58.70 Mpa sqrt(m)

Validation Criteria
Pmax 13.71 Pq 9.90 Pmax/Pq 1.39 Invalid
Through Thickness Constraint Invalid 11.92 < 28.129568
Remaining Ligament Constraint Invalid 16.90 < 28.129568

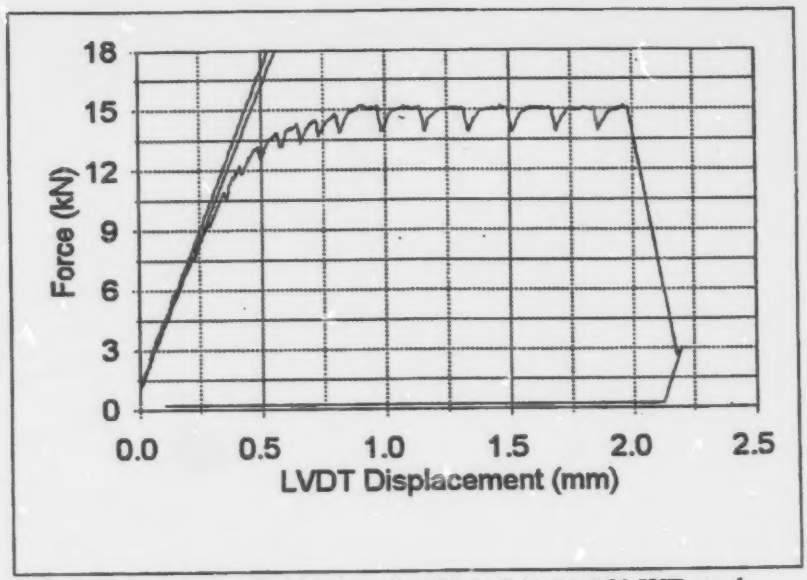

Figure K.3 - ASTM E-399 data for CSA G40.21 350 WT steel specimen #107 at -95 °C, T-L orientation.

TEST RESULTS

Specimen Identification: Specimen-8005-107
Material Type: 12mm_350WT_T-L_D
Material Yield: 350 Mpa

Specimen Dimensions

Specimen Width: 40.62 mm
Specimen Thickness: 11.93 mm
Specimen Span: 163.00 mm
Initial Specimen Compliance 31.99 mm/kN
Initial Crack Length Readings 23.45 mm 23.98 mm 23.00 mm
Average Crack Length 23.48 mm 0.577958 a/W Valid

Fracture Toughness Kq: 44.51 Mpa sqrt(m)

Validation Criteria
Pmax 14.89 Pq 7.68 Pmax/Pq 1.94 Invalid
Through Thickness Constraint Invalid 11.93 < 16.170076
Remaining Ligament Constraint Valid 17.14 > 16.170076

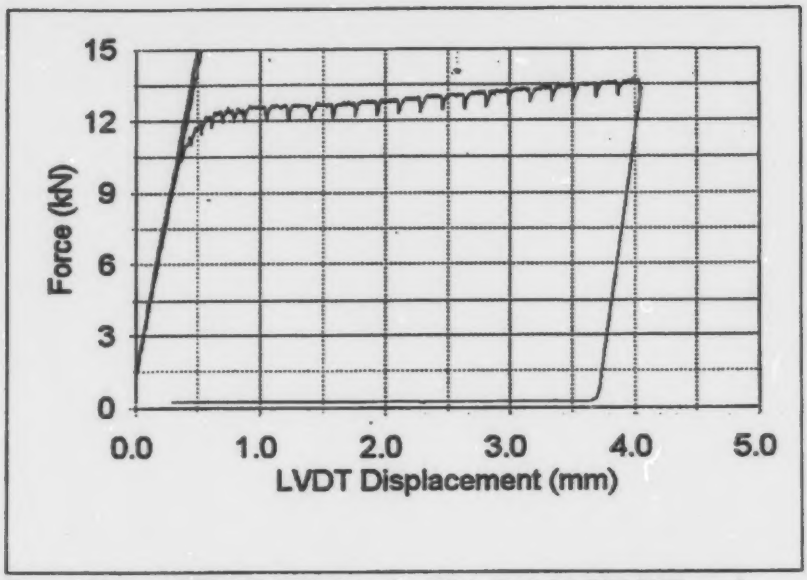

Figure K.4 - ASTM E-399 data for CSA G40.21 350 WT steel specimen #89 at -45 °C, L-T orientation.

TEST RESULTS

Specimen Identification: Specimen-8005-89
Material Type: 12mm_350WT_LTB
Material Yield: 350 Mpa

Specimen Dimensions

Specimen Width: 40.63 mm
Specimen Thickness: 12.01 mm
Specimen Span: 163.00 mm
Initial Specimen Compliance 27.29 mm/kN
Initial Crack Length Readings 23.67 mm 24.00 mm 23.59 mm
Average Crack Length 23.75 mm 0.584625 a/W Valid

Fracture Toughness Kq: 61.16 Mpa sqrt(m)

Validation Criteria
Pmax 13.45 Pq 10.37 Pmax/Pq 1.30 Invalid
Through Thickness Constraint Invalid 12.01 < 30.538750
Remaining Ligament Constraint Invalid 16.88 < 30.538750

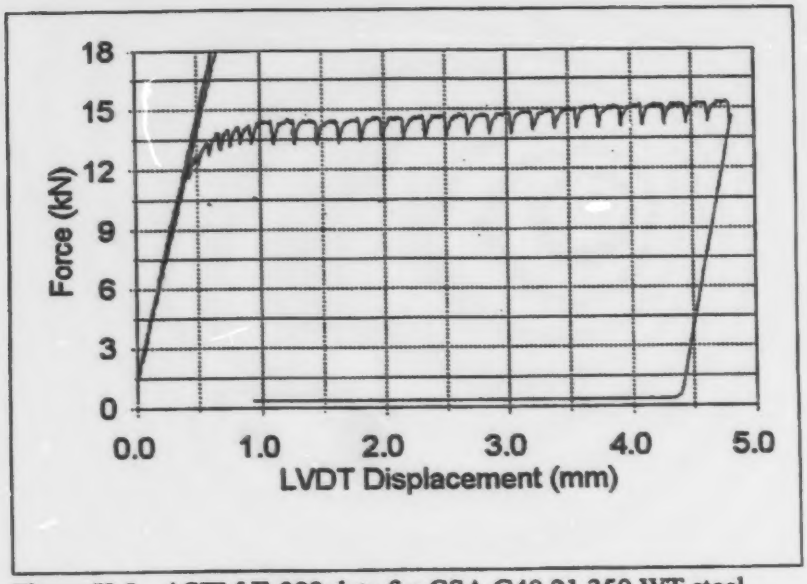

Figure K.5 - ASTM E-399 data for CSA G40.21 350 WT steel specimen #108 at -95 °C, L-T orientation.

TEST RESULTS

Specimen Identification: Specimen-8005-108
Material Type: 12mm_350WT_L-T_D
Material Yield: 350 Mpa

Specimen Dimensions

Specimen Width: 40.65 mm
Specimen Thickness: 12.03 mm
Specimen Span: 163.00 mm
Initial Specimen Compliance 26.70 mm/kN
Initial Crack Length Readings 23.83 mm 24.49 mm 24.19 mm
Average Crack Length 24.17 mm 0.594588 a/W Valid

Fracture Toughness Kq: 72.05 Mpa sqrt(m)

Validation Criteria
Pmax 14.98 Pq 11.80 Pmax/Pq 1.27 Invalid
Through Thickness Constraint Invalid 12.03 < 42.379414
Remaining Ligament Constraint Invalid 16.48 < 42.379414

Appendix L - ASTM E-399 Results for 8 mm 350WT Plate

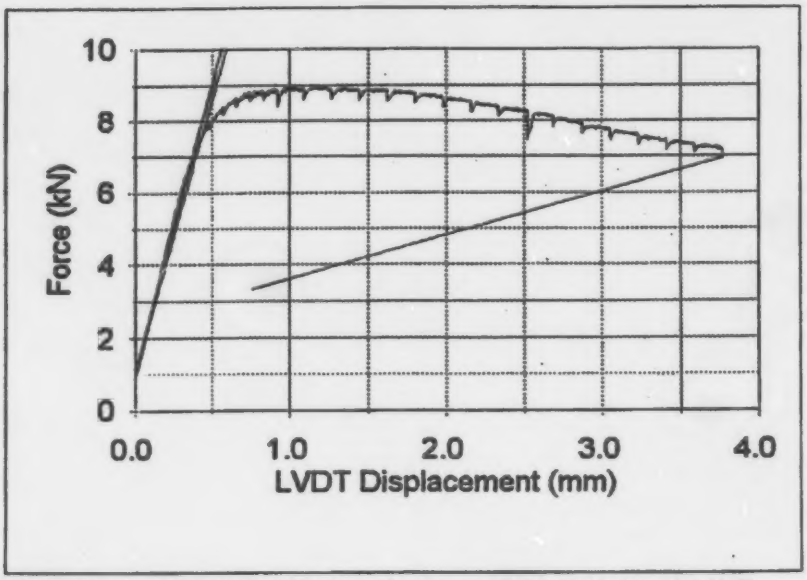

Figure L.1 - ASTM E-399 data for 8 mm CSA G40.21 350 WT steel specimen #97 at -10 °C, T-L orientation.

TEST RESULTS

Specimen Identification: Specimen-8005-97
Material Type: 8mm_350WT_TLD
Material Yield: 350 Mpa

Specimen Dimensions

Specimen Width: 40.65 mm
Specimen Thickness: 8.19 mm
Specimen Span: 163.00 mm
Initial Specimen Compliance 16.05 mm/kN
Initial Crack Length Readings 23.62 mm 23.98 mm 23.91 mm
Average Crack Length 23.84 mm 0.586388 a/W Valid

Fracture Toughness Kq: 68.70 Mpa sqrt(m)

Validation Criteria
Pmax 8.83 Pq 7.90 Pmax/Pq 1.12 Invalid
Through Thickness Constraint Invalid 8.19 < 38.522831
Remaining Ligament Constraint Invalid 16.81 < 38.522831

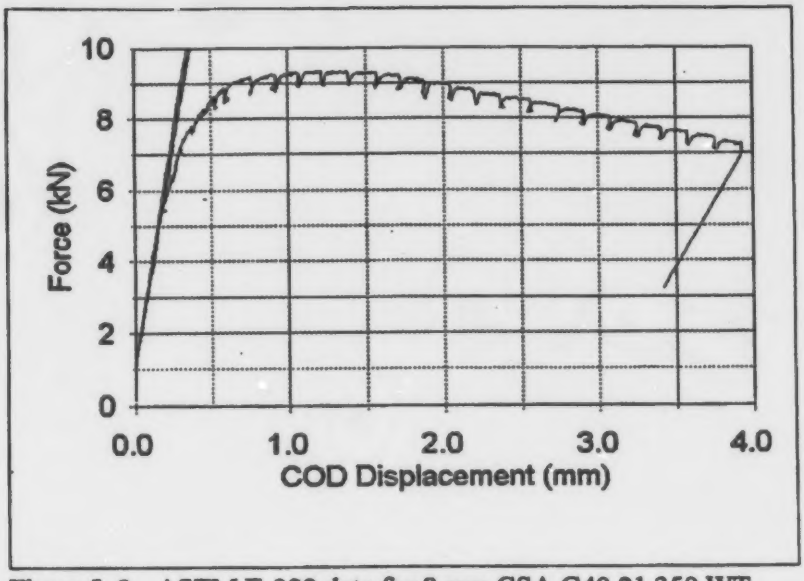

Figure L.2 - ASTM E-399 data for 8 mm CSA G40.21 350 WT steel specimen #93 at -25 °C, T-L orientation.

TEST RESULTS

Specimen Identification: Specimen-8005-93
Material Type: 8mm_350WT_TLc
Material Yield: 350 Mpa

Specimen Dimensions

Specimen Width: 40.64 mm
Specimen Thickness: 8.17 mm
Specimen Span: 163.00 mm
Initial Specimen Compliance 25.81 mm/kN
Initial Crack Length Readings 23.84 mm 24.22 mm 23.72 mm
Average Crack Length 23.93 mm 0.588747 a/W Valid

Fracture Toughness Kq: 19.91 Mpa sqrt(m)

Validation Criteria
Pmax 9.25 Pq 2.26 Pmax/Pq 4.09 Invalid
Through Thickness Constraint Valid 8.17 > 3.235206
Remaining Ligament Constraint Valid 16.71 > 3.235206

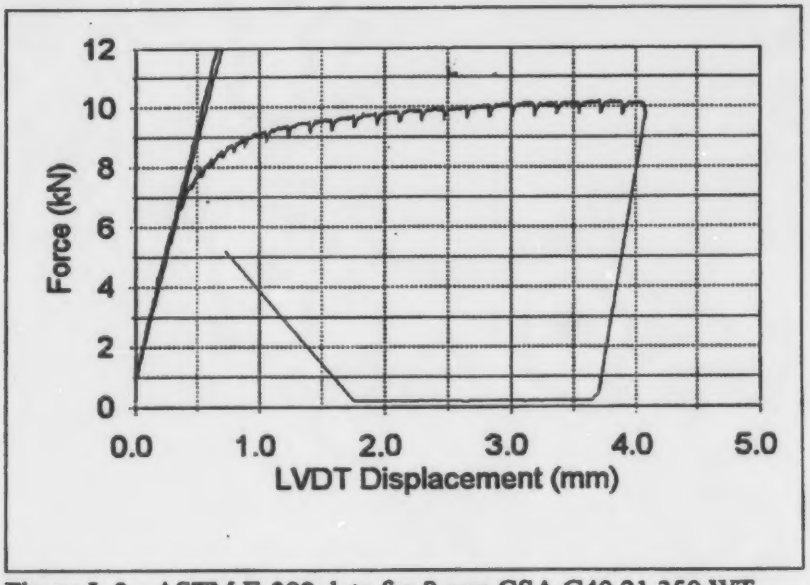

Figure L.3 - ASTM E-399 data for 8 mm CSA G40.21 350 WT steel specimen #94 at -35 °C, T-L orientation.

TEST RESULTS

Specimen Identification: Specimen-8005-94
Material Type: 8mm_350WT_LTB
Material Yield: 350 Mpa

Specimen Dimensions

Specimen Width: 40.60 mm
Specimen Thickness: 8.18 mm
Specimen Span: 163.00 mm
Initial Specimen Compliance 16.68 mm/kN
Initial Crack Length Readings 23.45 mm 23.75 mm 23.39 mm
Average Crack Length 23.53 mm 0.579557 a/W Valid

Fracture Toughness Kq: 56.74 Mpa sqrt(m)

Validation Criteria
Pmax 10.07 Pq 6.67 Pmax/Pq 1.51 Invalid
Through Thickness Constraint Invalid 8.18 < 26.280359
Remaining Ligament Constraint Invalid 17.07 < 26.280359

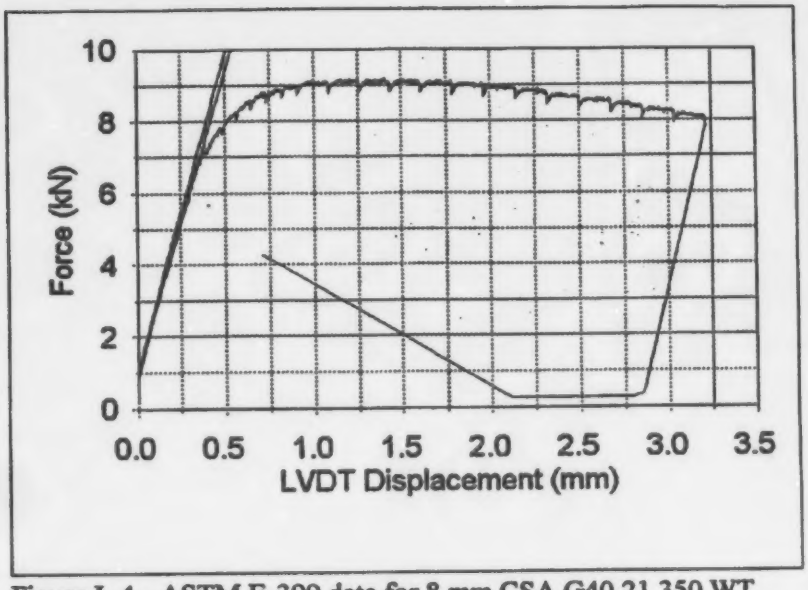

Figure L.4 - ASTM E-399 data for 8 mm CSA G40.21 350 WT steel specimen #90 at -35 °C, L-T orientation.

TEST RESULTS

Specimen Identification: Specimen-8005-90
Material Type: 8mm_350WT_TLB
Material Yield: 350 Mpa

Specimen Dimensions

Specimen Width: 40.61 mm
Specimen Thickness: 8.14 mm
Specimen Span: 163.00 mm
Initial Specimen Compliance 17.75 mm/kN
Initial Crack Length Readings 23.88 mm 24.33 mm 23.62 mm
Average Crack Length 23.94 mm 0.589592 a/W Valid

Fracture Toughness Kq: 56.71 Mpa sqrt(m)

Validation Criteria
Pmax 9.03 Pq 6.39 Pmax/Pq 1.41 Invalid
Through Thickness Constraint Invalid 8.14 < 26.255196
Remaining Ligament Constraint Invalid 16.67 < 26.255196

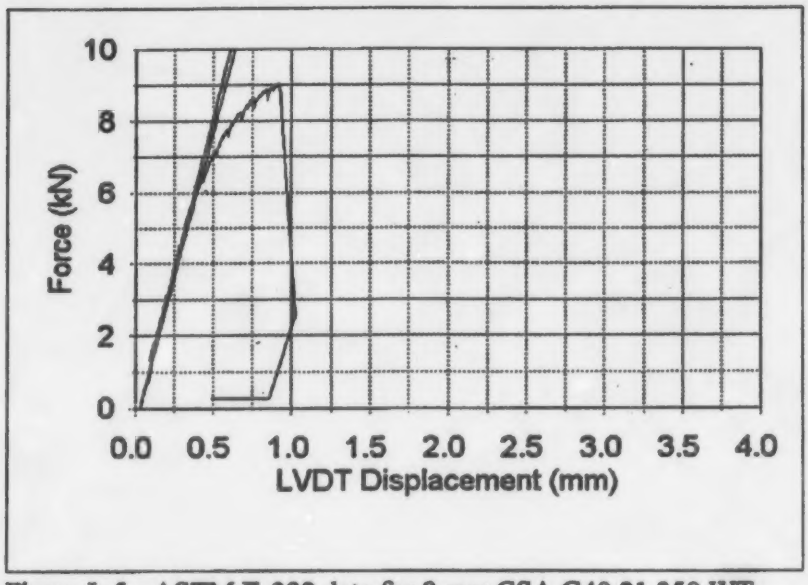

Figure L.5 - ASTM E-399 data for 8 mm CSA G40.21 350 WT steel specimen #91 at -50 °C, L-T orientation.

TEST RESULTS

Specimen Identification: Specimen-8005-91
Material Type: 8mm_350WT_LTD
Material Yield: 350 Mpa

Specimen Dimensions

Specimen Width: 40.62 mm
Specimen Thickness: 8.21 mm
Specimen Span: 163.00 mm
Initial Specimen Compliance 17.34 mm/kN
Initial Crack Length Readings 23.32 mm 23.83 mm 23.57 mm
Average Crack Length 23.57 mm 0.580338 a/W Valid

Fracture Toughness Kq: 54.34 Mpa sqrt(m)

Validation Criteria
Pmax 11.04 Pq 6.40 Pmax/Pq 1.73 Invalid
Through Thickness Constraint Invalid 8.21 < 24.105703
Remaining Ligament Constraint Invalid 17.05 < 24.105703

Appendix M - ASTM E-399 Results for 10 mm ASTM A517 Plate

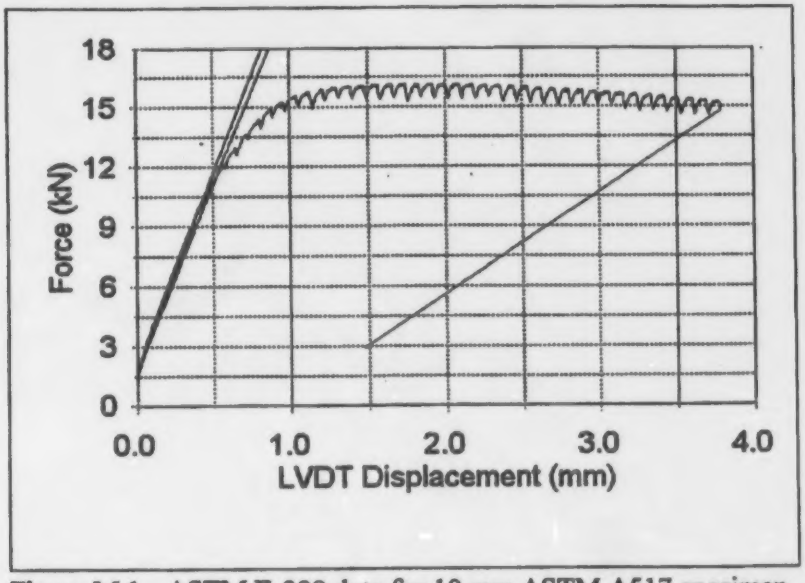

Figure M.1 - ASTM E-399 data for 10 mm ASTM A517 specimen #84 at -45 °C, T-L orientation.

TEST RESULTS

Specimen Identification: Specimen-8005-84
Material Type: ASTM_A517_TLB
Material Yield: 650 Mpa

Specimen Dimensions

Specimen Width: 40.61 mm
Specimen Thickness: 10.40 mm
Specimen Span: 163.00 mm
Initial Specimen Compliance 19.72 mm/kN
Initial Crack Length Readings 24.98 mm 25.49 mm 25.04 mm
Average Crack Length 25.17 mm 0.619798 a/W Valid

Fracture Toughness Kq: 94.65 Mpa sqrt(m)

Validation Criteria
Pmax 16.04 Pq 12.12 Pmax/Pq 1.32 Invalid
Through Thickness Constraint Invalid 10.40 < 21.203119
Remaining Ligament Constraint Invalid 15.44 < 21.203119

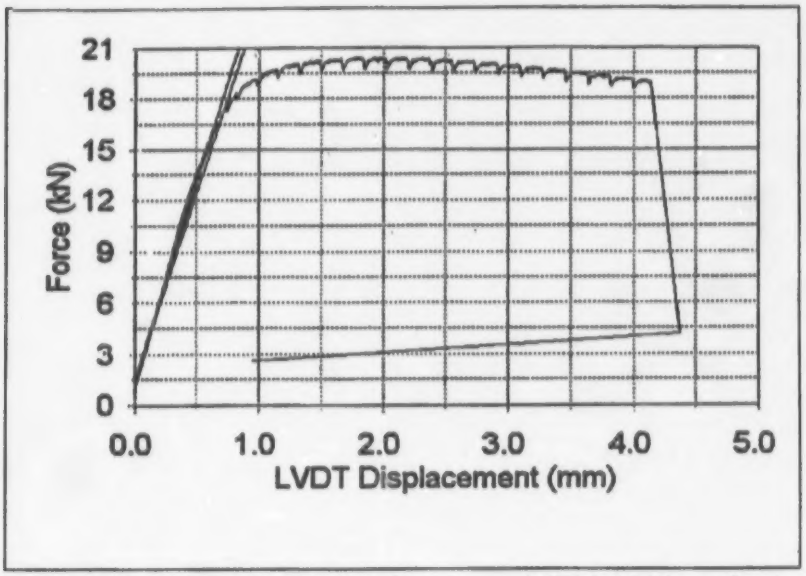

Figure M.2 - ASTM E-399 data for 10 mm ASTM A517 specimen #110 at -75 °C, T-L orientation.

TEST RESULTS

Specimen Identification: Specimen-8005-110
Material Type: A517_TL_C
Material Yield: 650 Mpa

Specimen Dimensions

Specimen Width: 40.57 mm
Specimen Thickness: 10.10 mm
Specimen Span: 163.00 mm
Initial Specimen Compliance 23.41 mm/kN
Initial Crack Length Readings 22.84 mm 23.53 mm 23.48 mm
Average Crack Length 23.28 mm 0.573905 a/W Valid

Fracture Toughness Kq: 117.52 Mpa sqrt(m)

Validation Criteria
Pmax 20.20 Pq 17.40 Pmax/Pq 1.16 Invalid
Through Thickness Constraint Invalid 10.10 < 32.687965
Remaining Ligament Constraint Invalid 17.29 < 32.687965

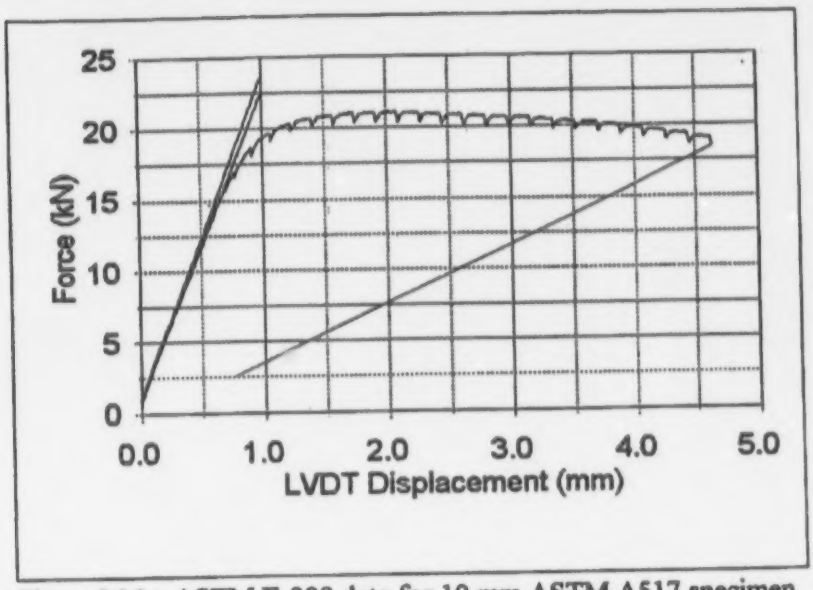

Figure M.2 - ASTM E-399 data for 10 mm ASTM A517 specimen #105 at -95 °C, T-L orientation.

TEST RESULTS

Specimen Identification: Specimen-8005-105
Material Type: A517_T-L_D
Material Yield: 650 Mpa

Specimen Dimensions

Specimen Width: 40.57 mm
Specimen Thickness: 10.11 mm
Specimen Span: 163.00 mm
Initial Specimen Compliance 22.77 mm/kN
Initial Crack Length Readings 23.12 mm 23.48 mm 23.38 mm
Average Crack Length 23.33 mm 0.574973 a/W Valid

Fracture Toughness Kq: 107.30 Mpa sqrt(m)

Validation Criteria
Pmax 20.93 Pq 15.84 Pmax/Pq 1.32 Invalid
Through Thickness Constraint Invalid 10.11 < 27.248882
Remaining Ligament Constraint Invalid 17.24 < 27.248882

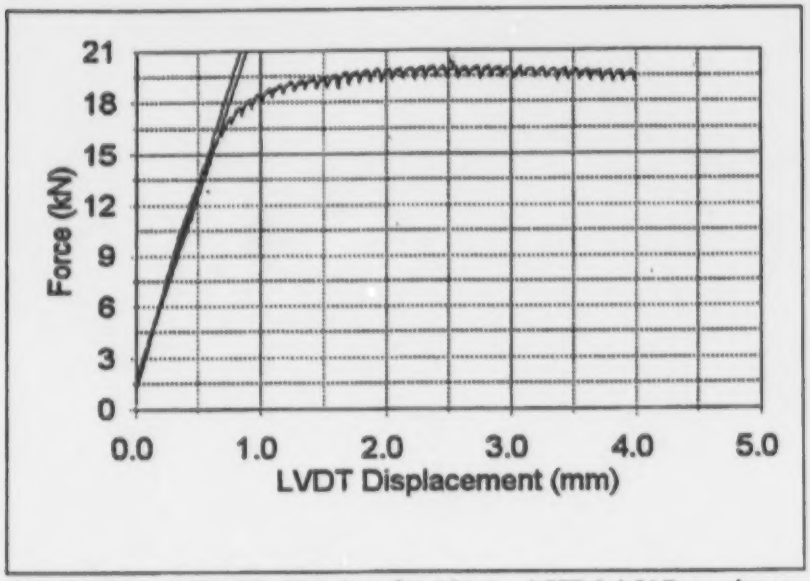

Figure M.4 - ASTM E-399 data for 10 mm ASTM A517 specimen #83 at -55 °C, L-T orientation.

TEST RESULTS

Specimen Identification: Specimen-8005-83
Material Type: ASTM_A517_LTB
Material Yield: 650 Mpa

Specimen Dimensions

Specimen Width: 40.62 mm
Specimen Thickness: 10.40 mm
Specimen Span: 163.00 mm
Initial Specimen Compliance 23.01 mm/kN
Initial Crack Length Readings 23.73 mm 23.81 mm 23.53 mm
Average Crack Length 23.69 mm 0.583210 a/W Valid

Fracture Toughness Kq: 110.13 Mpa sqrt(m)

Validation Criteria
Pmax 19.87 Pq 16.25 Pmax/Pq 1.22 Invalid
Through Thickness Constraint Invalid 10.40 < 28.708321
Remaining Ligament Constraint Invalid 16.93 < 28.708321

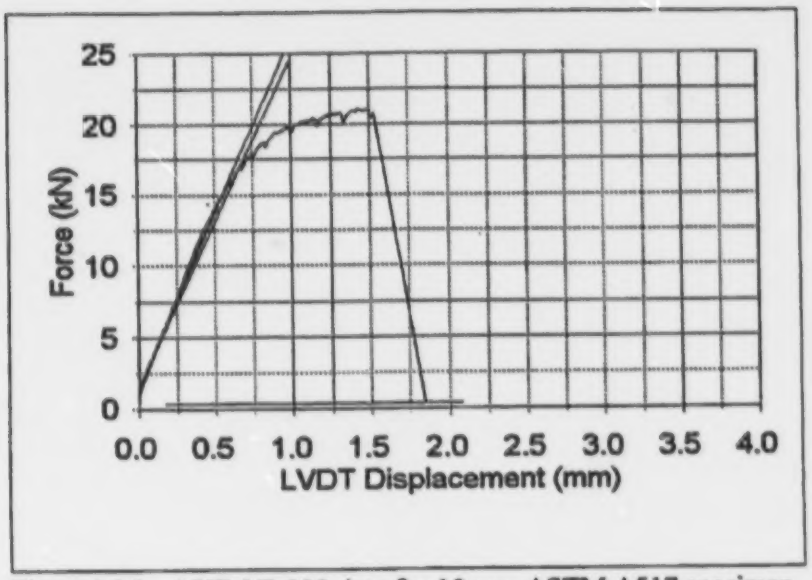

Figure M.5 - ASTM E-399 data for 10 mm ASTM A517 specimen #109 at -95 °C, L-T orientation.

TEST RESULTS

Specimen Identification: Specimen-8005-109
Material Type: A517_L-T_C
Material Yield: 650 Mpa

Specimen Dimensions

Specimen Width: 40.65 mm
Specimen Thickness: 10.24 mm
Specimen Span: 163.00 mm
Initial Specimen Compliance 24.51 mm/kN
Initial Crack Length Readings 23.35 mm 23.85 mm 23.71 mm
Average Crack Length 23.64 mm 0.581468 a/W Valid

Fracture Toughness Kq: 115.84 Mpa sqrt(m)

Validation Criteria
Pmax 20.86 Pq 16.96 Pmax/Pq 1.23 Invalid
Through Thickness Constraint Invalid 10.24 < 31.759771
Remaining Ligament Constraint Invalid 17.01 < 31.759771

Appendix N - ASTM E-399 Results for Various Weldments

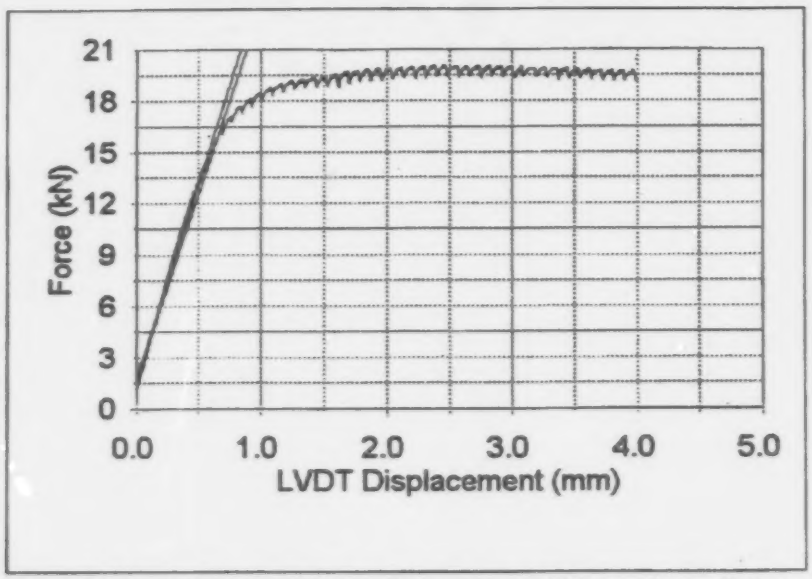

Figure N.1 - ASTM E-399 data for weldment W3 specimen #85 at -50 °C.

TEST RESULTS

Specimen Identification: Specimen-8005-85
Material Type: 350WT_WELD_3
Material Yield: 350 Mpa

Specimen Dimensions

Specimen Width: 40.56 mm
Specimen Thickness: 9.06 mm
Specimen Span: 163.00 mm
Initial Specimen Compliance 17.78 mm/kN
Initial Crack Length Readings 24.07 mm 24.31 mm 23.96 mm
Average Crack Length 24.11 mm 0.594510 a/W Valid

Fracture Toughness Kq: 47.77 Mpa sqrt(m)

Validation Criteria
Pmax 11.48 Pq 5.87 Pmax/Pq 1.95 Invalid
Through Thickness Constraint Invalid 9.06 < 18.626841
Remaining Ligament Constraint Invalid 16.45 < 18.626841

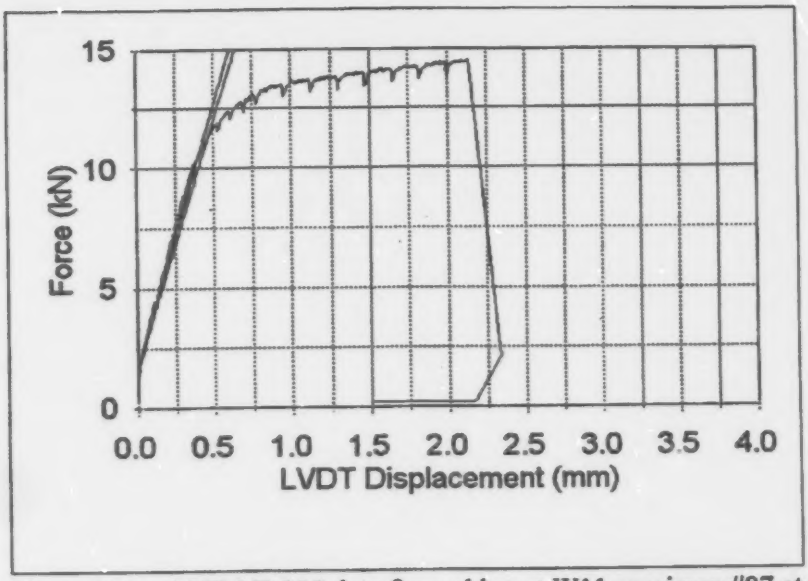

Figure N.2 - ASTM E-399 data for weldment W11 specimen #87 at -50 °C.

TEST RESULTS

Specimen Identification: Specimen-8005-87
Material Type: 350WT_WELD_11
Material Yield: 350 Mpa

Specimen Dimensions

Specimen Width: 40.80 mm
Specimen Thickness: 11.83 mm
Specimen Span: 163.00 mm
Initial Specimen Compliance 21.96 mm/kN
Initial Crack Length Readings 25.00 mm 24.64 mm 23.23 mm
Average Crack Length 24.29 mm 0.595343 a/W Valid

Fracture Toughness Kq: 73.08 Mpa sqrt(m)

Validation Criteria
Pmax 14.24 Pq 11.80 Pmax/Pq 1.21 Invalid
Through Thickness Constraint Invalid 11.83 < 43.596752
Remaining Ligament Constraint Invalid 16.51 < 43.596752

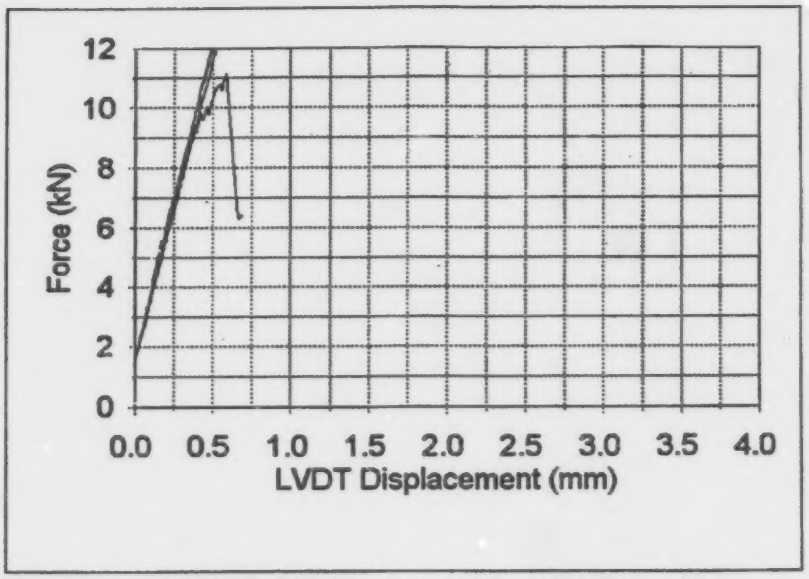

Figure N.3 - ASTM E-399 data for weldment W12B specimen #104 at -40 °C.

TEST RESULTS

Specimen Identification: Specimen-8005-104
Material Type: 350WT_Weld_12B
Material Yield: 350 Mpa

Specimen Dimensions

Specimen Width: 40.75 mm
Specimen Thickness: 11.85 mm
Specimen Span: 163.00 mm
Initial Specimen Compliance 21.50 mm/kN
Initial Crack Length Readings 24.49 mm 24.43 mm 23.89 mm
Average Crack Length 24.27 mm 0.595583 a/W Valid

Fracture Toughness Kq: 57.97 Mpa sqrt(m)

Validation Criteria
Pmax 10.77 Pq 9.35 Pmax/Pq 1.15 Invalid
Through Thickness Constraint Invalid 11.85 < 27.430824
Remaining Ligament Constraint Invalid 16.48 < 27.430824

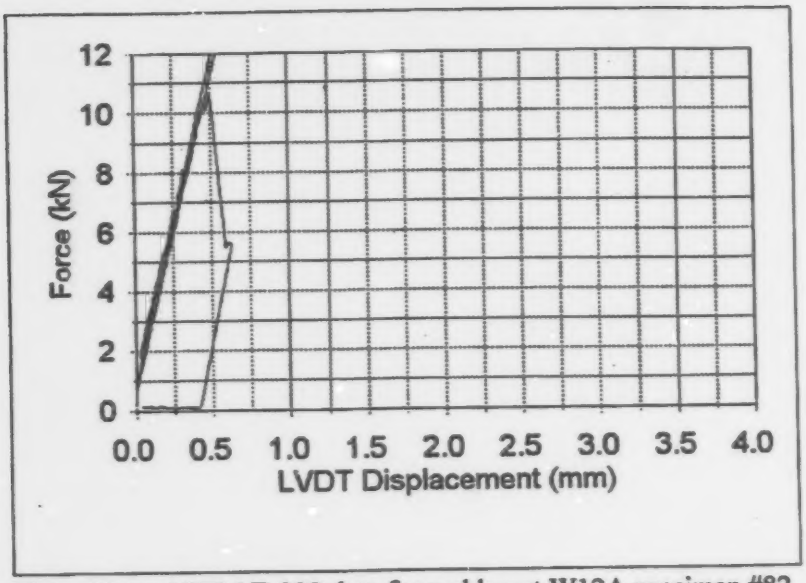

Figure N.4 - ASTM E-399 data for weldment W12A specimen #82 at -50 °C.

TEST RESULTS

Specimen Identification: Specimen-8005-82
Material Type: 350WT_Weld_12A
Material Yield: 350 Mpa

Specimen Dimensions

Specimen Width: 40.64 mm
Specimen Thickness: 11.43 mm
Specimen Span: 163.00 mm
Initial Specimen Compliance 22.48 mm/kN
Initial Crack Length Readings 24.12 mm 24.06 mm 23.35 mm
Average Crack Length 23.84 mm 0.586696 a/W Valid

Fracture Toughness Kq: 63.32 Mpa sqrt(m)

Validation Criteria
Pmax 10.30 Pq 10.14 Pmax/Pq 1.01 Valid
Through Thickness Constraint Invalid 11.43 < 32.732342
Remaining Ligament Constraint Invalid 16.80 < 32.732342

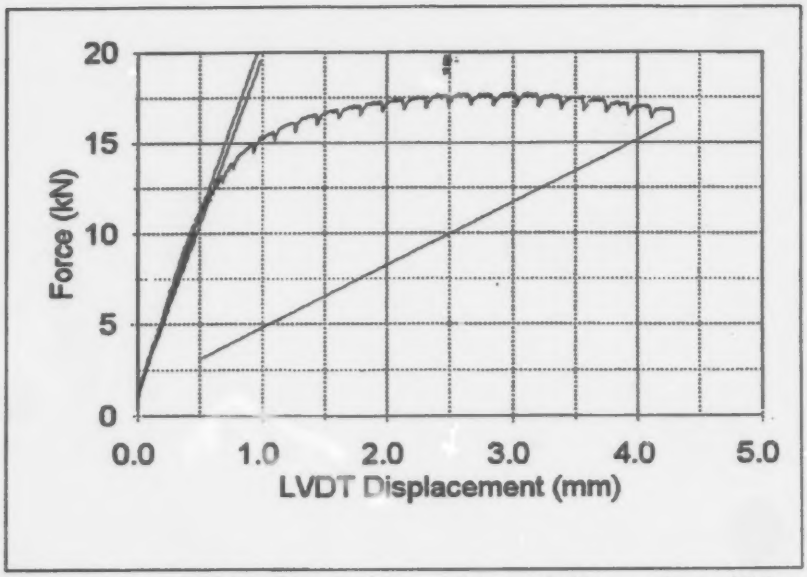

Figure N.5 - ASTM E-399 data for weldment W20 specimen #86 at -40 °C.

TEST RESULTS

Specimen Identification: Specimen-8005-86
Material Type: A517_WELD_20
Material Yield: 350 Mpa

Specimen Dimensions

Specimen Width: 40.70 mm
Specimen Thickness: 10.64 mm
Specimen Span: 163.00 mm
Initial Specimen Compliance 19.51 mm/kN
Initial Crack Length Readings 23.81 mm 24.03 mm 23.86 mm
Average Crack Length 23.90 mm 0.587224 a/W Valid

Fracture Toughness Kq: 82.00 Mpa sqrt(m)

Validation Criteria
Pmax 17.58 Pq 12.23 Pmax/Pq 1.44 Invalid
Through Thickness Constraint Invalid 10.64 < 54.886948
Remaining Ligament Constraint Invalid 16.80 < 54.886948

Appendix O - Elastic-Plastic Results for Lloyds Grade A Steel.

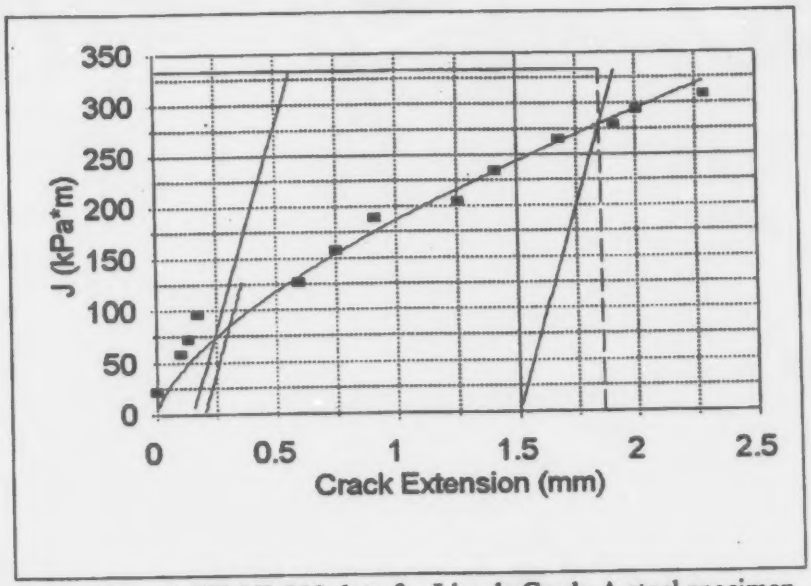

Figure O.1 - ASTM E-813 data for Lloyds Grade A steel specimen #100 at 22 °C, T-L orientation.

TEST RESULTS

Provisional Jq (kJ/m2) = 85.23
Through thickness constraint valid (B=12.49) > 5.33
Remaining Ligament constraint valid (bi=16.81) > 5.33
dJ/da (184.49) is less than yield (400.00) (valid)
Fatigue precrack straightness invalid 23.89 (mm)
Crack extension straightness invalid 26.32 (mm)
Compliance accuracy measurement valid

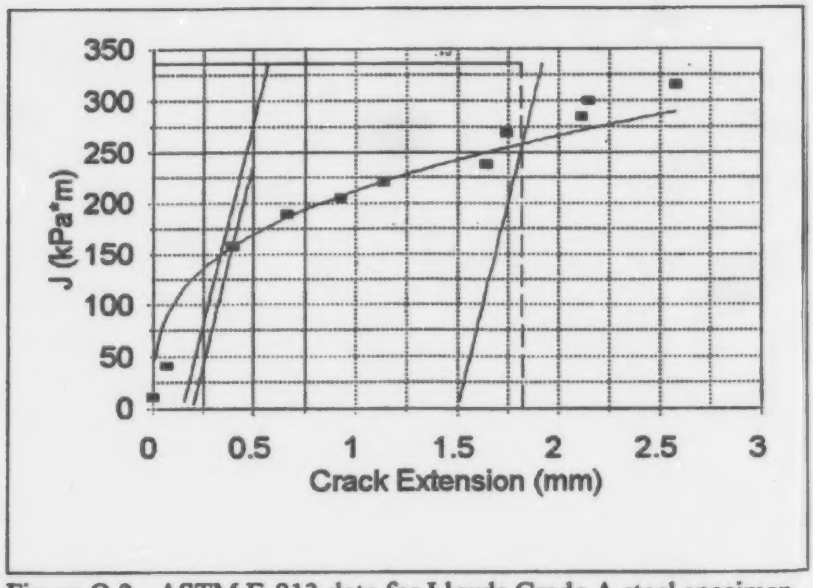

Figure O.2 - ASTM E-813 data for Lloyds Grade A steel specimen #99 at 0 ^{0}C, T-L orientation.

TEST RESULTS

Provisional Jq (kJ/m2) = 157.35
Through thickness constraint valid (B=12.60) > 9.83
Remaining Ligament constraint valid (bi=16.98) > 9.83
dJ/da (129.67) is less than yield (400.00) (valid)
Fatigue precrack straightness valid 23.71 (mm)
Crack extension straightness valid 25.40 (mm)
Compliance accuracy measurement valid
Jq = JIC

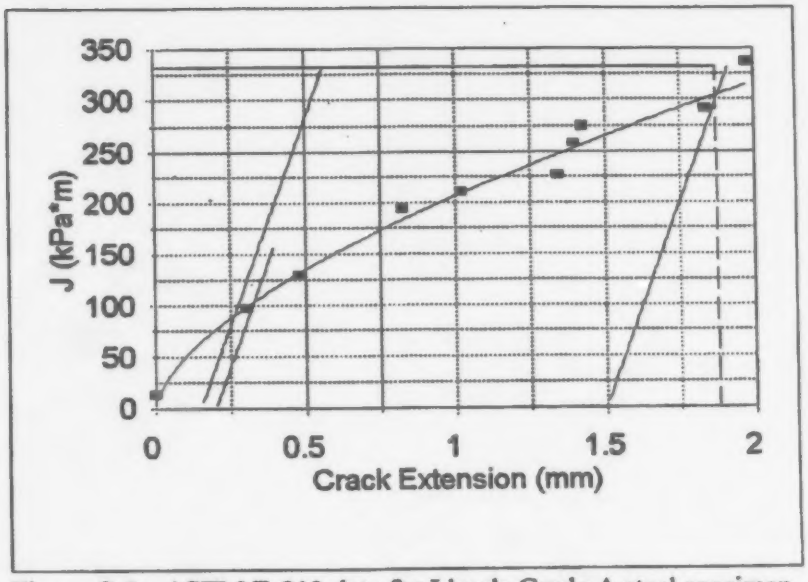

Figure O.3 - ASTM E-813 data for Lloyds Grade A steel specimen #96 at -20 °C, T-L orientation.

TEST RESULTS

Provisional Jq (kJ/m2) = 104.12
Through thickness constraint valid (B=12.46) > 6.51
Remaining Ligament constraint valid (bi=16.71) > 6.51
dJ/da (195.28) is less than yield (400.00) (valid)
Fatigue precrack straightness invalid 23.91 (mm)
Crack extension straightness invalid 26.37 (mm)
Compliance accuracy measurement valid

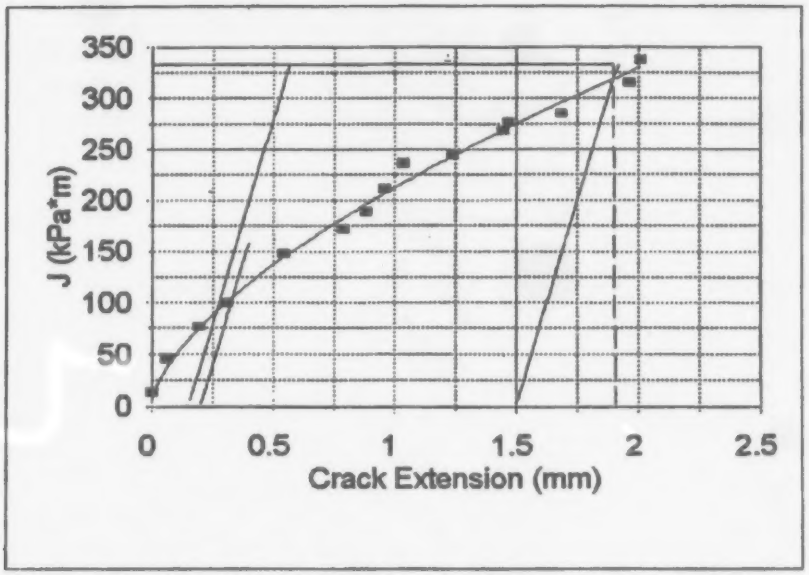

Figure O.4 - ASTM E-813 data for Lloyds Grade A steel specimen #81 at -40 °C, T-L orientation.

TEST RESULTS

Provisional Jq (kJ/m2) = 105.85
Through thickness constraint valid (B=12.51) > 6.62
Remaining Ligament constraint valid (bi=16.59) > 6.62
dJ/da (202.23) is less than yield (400.00) (valid)
Fatigue precrack straightness valid 24.12 (mm)
Crack extension straightness valid 26.00 (mm)
Compliance accuracy measurement valid
Jq = JIC

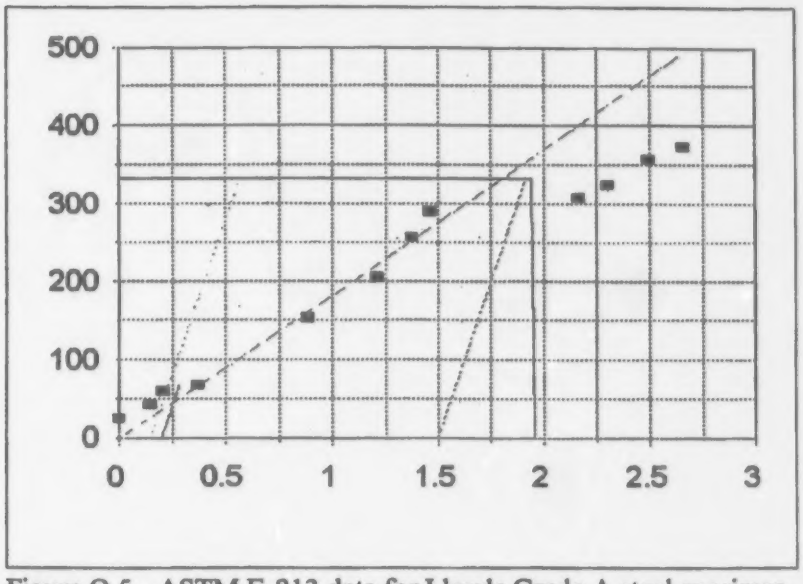

Figure O.5 - ASTM E-813 data for Lloyds Grade A steel specimen #102 at -55 °C, T-L orientation.

TEST RESULTS

Provisional Jq (kJ/m2) = 45.40
Through thickness constraint valid (B=12.45) > 2.84
Remaining Ligament constraint valid (bi=17.10) > 2.84
dJ/da (180.72) is less than yield (400.00) (valid)
Fatigue precrack straightness valid 23.64 (mm)
Crack extension straightness invalid 26.83 (mm)
Compliance accuracy measurement valid

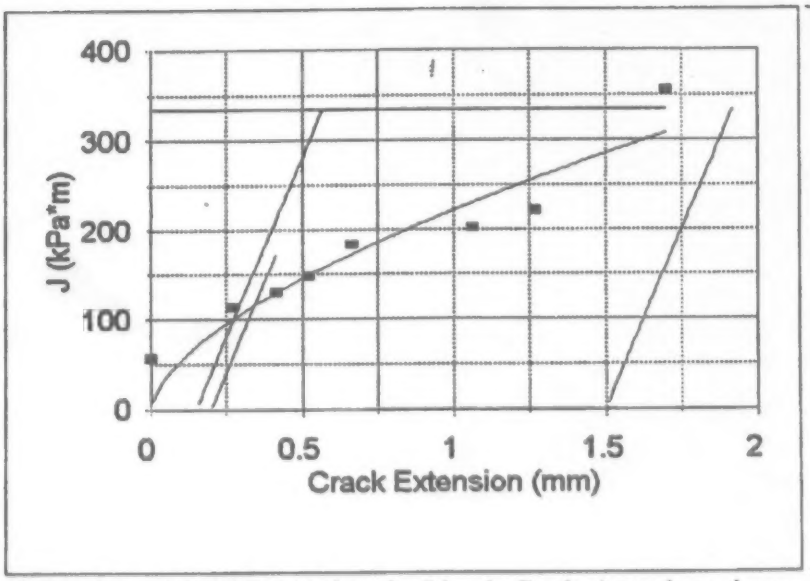

Figure O.6 - ASTM E-813 data for Lloyds Grade A steel specimen #95 at -20 °C, L-T orientation.

TEST RESULTS

Provisional Jq (kJ/m2) = 115.30
Through thickness constraint valid (B=12.53) > 7.21
Remaining Ligament constraint valid (bi=17.09) > 7.21
dJ/da (206.90) is less than yield (400.00) (valid)
Fatigue precrack straightness invalid 23.32 (mm)
Crack extension straightness invalid 24.77 (mm)
Compliance accuracy measurement valid

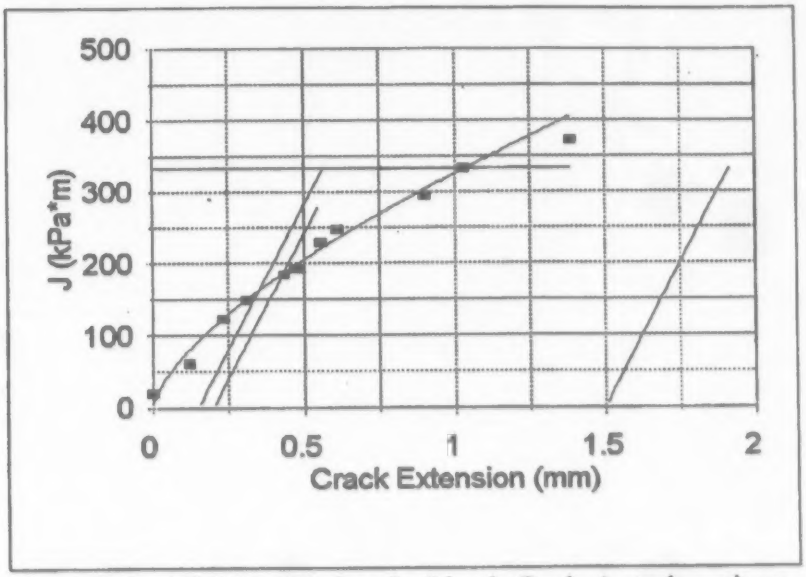

Figure O.7 - ASTM E-813 data for Lloyds Grade A steel specimen #80 at -40 °C, L-T orientation.

TEST RESULTS

Provisional Jq (kJ/m2) = 186.20
Through thickness constraint valid (B=12.50) > 11.64
Remaining Ligament constraint valid (bi=17.02) > 11.64
dJ/da (288.16) is less than yield (400.00) (valid)
Fatigue precrack straightness valid 23.69 (mm)
Crack extension straightness valid 24.50 (mm)
Compliance accuracy measurement valid
Jq = JIC

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Material temperature transition curves are a necessary requirement for the understanding of the response of structures exposed to various temperatures, loading rates, and stress states. DREA has relied heavily on ASTM standard E-604 to produce transition information for steels and weldments of relevance to the Canadian Navy. This report focuses on the relationship between ASTM E-604 transition curves and quantitative elastic and elastic-plastic fracture properties, namely, K and J-integral, respectively. The materials evaluated include marine steel plates and weldments with varying flow properties, including Lloyds Grade A plate, CSA G40.21 350WT, and ASTM A517. A comparison of the ASTM E-604 transition temperature and the transition temperature for specimens tested at quasistatic loading rates indicates a significant shift to lower transition temperatures for the quasistatic specimens. This shift was attributed to the difference in applied loading rates between the two tests. Elastic and elastic-plastic analyses of the 350WT and A517 test samples indicate that as the temperature decreases, the failure mechanism changes from ductile stable limit load tearing to brittle unstable crack propagation. There was no temperature interval for the materials in the thicknesses tested where crack initiation was governed by either K or J as defined by ASTM E-399 and ASTM E-813, respectively.

The Lloyds Grade A plate material in the T-L orientation produced J controlled crack initiation down to -55°C. For the L-T orientation, the specimen tested at 0°C generated crack extensions by limit load tearing. In the temperature interval from -20°C to -40°C, the specimen produced J controlled crack initiation. The specimens tested at -55°C and -70°C initiated brittle instabilities after significant plasticity.

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